SULPHUR BEARING SALT DOMES OF THE GULF COAST REGION AND THE ASSOCIATED FRASCH SULPHUR INDUSTRY

Written by:

Geoffrey Roger Leking

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INTRODUCTION

My thesis describes those salt domes of the Gulf Coast Region which contain commercial sulphur deposits, as well as the associated Frasch sulphur industry. The origin, structure, and composition of the Gulf Coast salt domes is first discussed. A generous portion of this discussion is devoted to the cap rock where the sulphur is deposited. A profile of the nature of sulphur is then undertaken, followed by a description of Herman Frasch, his process, and the development of the Frasch sulphur industry up to the present. Predictions for the future of the industry, and a final summary of the industry's development conclude the paper.

SALT BASIN ORIGIN

Frasch sulphur is mined from the cap rocks overlying salt dome structures found most extensively in the Gulf Coast Region of North America. There are also recently developed Frasch operations in Poland and the Soviet Union. An explanation of the origin of the salt basin, salt dome structures, and their cap rock is necessary background for the understanding of the occurrence of sulphur in these structures.

A salt basin is the result of an evaporative process performed on marine water. This process results in an evaporite depositional sequence. The evaporite sequence is characterized by the precipitation of the least soluble compounds first ((calcium carbonate-limestone) and (calcium sulphate-gypsum and anhydrite)) followed by the precipitation of the more soluble salts (halite (NaCl) and then potassium and magnesium salts). Pettijohn stated that in a 1,000 foot column of present day seawater a total of fifteen feet of evaporite will be precipitated from this solution. This evaporite is composed of 0.4 feet of calcium sulphate, 11.6 feet of halite, and 3.0 feet of the lighter element salts.[1] In nature all or just part of this sequence can be found, and its occurrence depends upon brine concentration, temperature, and solubility of the salts in brine. The final variables affecting the deposition of evaporites are depth of water, bathymetry of the basin, time of evaporation and geomorphological characteristics of adjacent land bodies.[2]

These variables are integrated into Ochsenius' "bar theory" for the deposition of evaporites. Thick sequences are formed in basins where evaporation defeats rainfall and surface run-off, and marine waters are restricted from supplying the evaporite pool with fresh unconcentrated solution due to some sort of barrier. Replenishment, with unconcentrated solution to the basin, occurs only when storm flood waters ascend over the basin's seaward barrier. These events take place over an extensive span of geologic time.[3]

The salt basin underlying the Gulf Region of East Texas and Louisiana, and from which the Region's salt dome structures extend into the overlying basin sediments is named the Louann salt. The Louann salt is considered to be either Permian in age or to range from Triassic to Middle Jurassic in age. There is substantial evidence provided for each of these hypotheses.

The belief that the Louann salt is Permian in age is the older of the two hypotheses.[4] General evidence supporting this hypothesy begins with the consideration of the period's climate. The Permian was a period of extreme aridity which prevailed for a great length of time. There are Permian evaporite sequences distributed across the globe. Several of these display great accumulations of salt similar to the Louann. A particularly analagous salt basin is the Zechstein Salt of northern Germany which has an extensive area of salt dome structures extending from the Zechstein "mother bed" of salt. The West Texas Permian salt basin lends credence to the speculated Permian age of the Louann due to its proximity to the Gulf area.

Development of the Louann is chiefly believed to have evolved from interconnecting barred basins according to Branson's model (1915).[5] The carbonates and sulphates are first precipitated in one barred basin, after which the marine waters flow to the neighboring barred basin where the hypersaline salts are precipitated.

The deposition of the Louann salt basin originated because of hypersaline waters flowing in from the west.[6] The source of these waters was the Castile Sea situated in the Delaware basin in what is now west Texas. The

Castile formation was deposited in this basin in the form of calcium sulphate (anhydrite) and calcium carbonate (limestone). These sulphates and carbonates were deposited until the water's concentration approached the point of NaCl precipitation. An influx of marine water would flood over the bar barrier at the south area of the Delaware Basin supplied by a shallow marine sea in the south and the southwest. These marine waters driven by storm action arrived with sufficient force to displace the hypersaline waters into the east. The hypersaline waters probably flowed along a southeast trending channel to the south of Texas' Central Mining Region. They reached the Louann-Werner Basin (Gulf Coast Basin) and were then evaporated leaving behind sodium chloride salt.

Two more stratigraphic features help in supporting this model.[7] An unconformity at the base of the Werner Formation correlates with an unconformity at the base of the Castile Formation. A hiatus between the Louann salt and Norphelt Formation represents post Castile Permian time, all of Triassic, and Lower and Middle Jurassic time. It is suspected that the channel was permanently closed prior to Salado time (Hazzard et al., 1947).

Halbouty and Hardin (1956) expanded on Hazzard's work. Their model first described the Gulf salt basin area to have subsided with the extensive Llanoria landmass of the Ouachita tectonic province. This was the beginning of the Gulf coast geosyncline and the present day Gulf of Mexico. The subsidence continued through the Lower and Middle Permian time and formed a large restricted basin.[8]

The seas of west Texas, due to the arid climate, were also restricted, and the Delaware basin was the only submerged feature at the beginning of Castile time (Upper Permian). Lowlands surrounded the Delaware basin and tidal flats were found in the east. These tidal flats experienced no new sedimentation or erosion during this period and had narrow flow channels running through them. These narrow channels contained intermittent permeable barriers, and this flow system resulted in the connection of the Gulf coast basin and the Castile sea. The same shallow marine sea existed to the southwest of the bar cordoning off the Delaware Basin.[9]

Marine water entered the Castile Sea from the south or southwest through one or more narrow channels. A sand dune ridge composed of calcareous sands and organic reef probably composed the barrier. This barrier was overcome by seasonal storm waves and closed by normal wind action. These storm waves contained sufficient force to eject the concentrated brines into the eastern tidal flat channels and on into the Gulf Coast basin. The water was evaporated and halite accumulated. The repetitive cycle caused the absence of halite in the Castile anhydrite of the Delaware Basin and the absence of anhydrite in the Louann Salt in the Gulf Coast Basin[10] (Hazzard et al.).

The hypothesis of an Upper Triassic--Lower Jurassic age dating of the Louann salt is the most widely believed hypothesis. The main thrust of evidence is presented by Murray (1961).

Correlative evidence stems from the clastic-evaporite sequence of eastern and southern Mexico in the southwestern portion of the Rio Grande embayment. Imlay et al. (1948),[11] correlated the red beds of the Huizachal formation (probably Lower-Middle Jurassic) with the Eagle Mills Formation of the Gulf region. The Louann is thought to be equivalent to the disconformity between the Huizachal Formation and overlying Upper Oxfordian limestone in east and north Mexico. The Huizachal Group spottily overlies early Jurassic strata, and Huizachal red beds yield Middle Jurassic-Triassic plant fossils.

The Eagle Mills-Werner-Louann underlie Late Jurassic Smackover and Norphelt Formations and lie over Paleozoic (Permian and older) and Paleozoic Precambrian. Correlation can be made between a formation of over 2000 feet of evaporite, mainly composed of anhydrite, which exists in the Sabinas Basin in northeastern Mexico. The evaporite underlies the Zuloaga limestone, an equivalent to the Smackover Formation of Upper Jurassic Oxfordian age. The sulphate concentrate is equivalent to the Louann salt.[12]

A structural correlation between the Louann salt and other thick accumulations of salt in the coastal area, and thick Late Jurassic deposits is made through their proximity to an inner-boundary fault system.[13] The salts are restricted basinward as is the inner extent of the Late Jurassic deposits.

Fossil evidence has been widely used to date the Louann salt.[14] Salt domes in northern Cuba have produced spores of Mesozoic age which are no younger than Early Cretaceous. Red algae of the Permian was found at Markham, Matagorda County, Texas, in 1924. The plant fossil Macrotaeniopteris magnifolic has been found in the Eagle Mills formation of southern Arkansas. Since the Louann salt is stratigraphically above the Eagle Mills formation it can be no older than Upper Traissic and is probably Early to Middle Jurassic in age. Spores of predominantly Upper Triassic types have been found in salt mines of Texas and Louisiana along with lower Jurassic age spores. All of this fossil evidence strongly supports the Louann salt's age as being Upper Triassic to Lower Jurassic. This dating has become accepted theory by the majority of geologists.

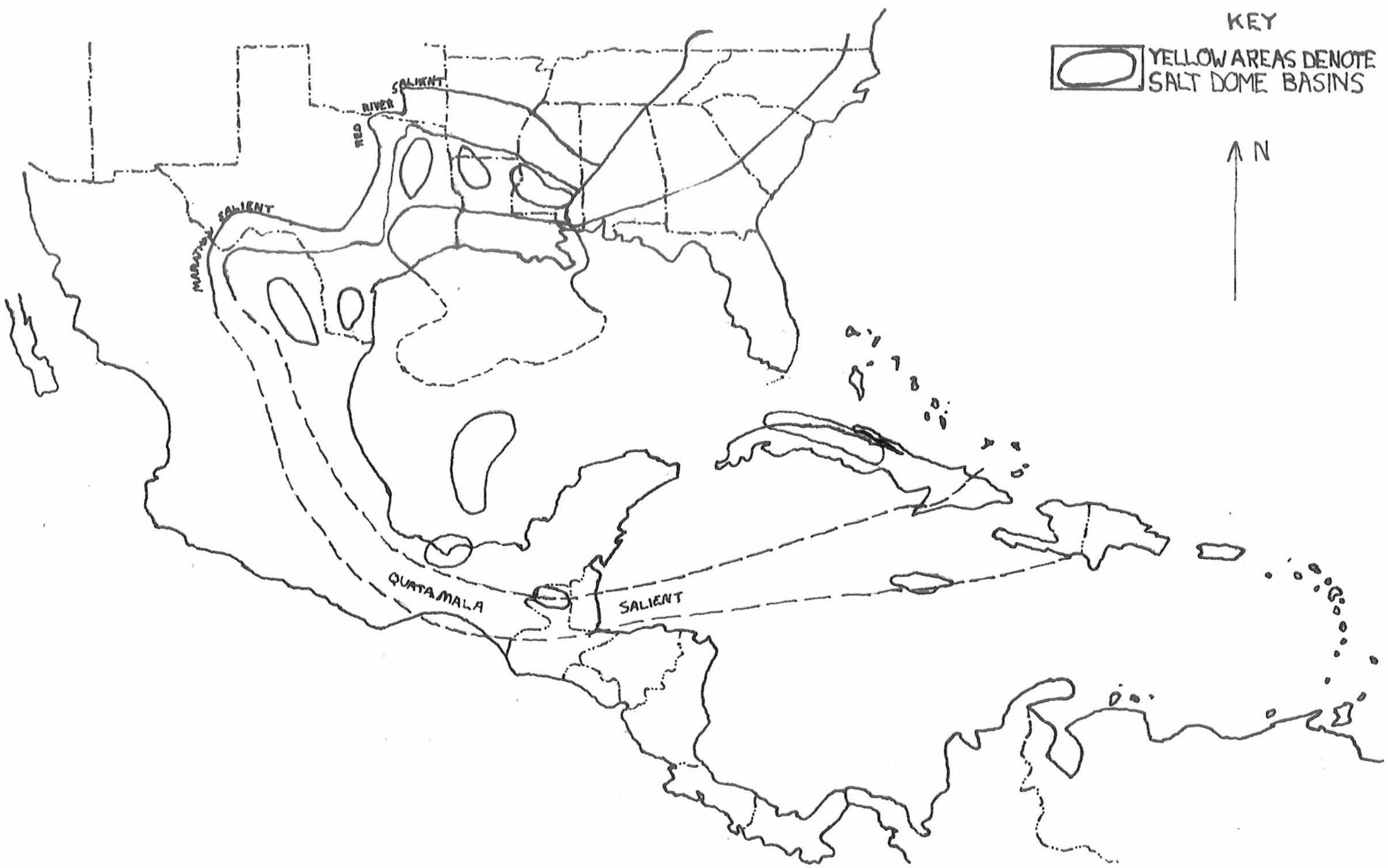
The deposition and structural development of these Mesozoic salt basins and salt dome basins came after the Ouachita Orogeny which ended in Upper Permian time. This orogenic activity and its Mexican and Antillean counterparts were responsible for controls set on the structural relationships and tectonic features of the Gulf region.[15] Zones of faulting on the inner edge of the Gulf region and zones of igneous activity of Cretaceous and younger time follow the Ouachita trend.

The Ouachita structural belt influences positive and negative elements of the inner margin of the Gulf Region.[16] These negative and positive elements are the result of the Ouachita tectonic belt curving toward and over the craton and displaying broad salients and recesses. Mexico and Northern Central America correspondingly display salients of the Paleozoic tectonic belt against positive elements of the coastal province and recesses adjacent to negative elements.

The salt dome basins of VeraCruz-Tabasco, Rio Grande, East Texas, North Louisiana, and the Louisiana-Mississippi basins are all depocenters within salt basins adjacent to arc salients of Paleozoic orogenic belts like the Ouachita Orogney.[17] The maximum deposition within these basins are located at weak crustal zones which subsided during isostatic adjustment to the Paleozoic orogeny.

The Louann salt underlies the Gulf region including the Gulf of Mexico. The single salt basin originated from an ancient barred gulf (Lyons, 1957; and Imlay, 1943). This was an extensive area which has given rise to a topography within the salt where domeless plains separate dome basins and major tectonic features. A thin layer of the Louann salt covers these plains.[18] Localized areas within the basin contain no salt where erosion, non-deposition, or flowage from high to low points may have taken place.

The tectonic features within the basin control salt deposition and salt structure growth.[19] The San Marcos arch of Southeast Texas is a good example of a tectonic control of salt deposition and salt structure building.



KNOWN SALT DOME BASINS AND THE ARC SALIENTS OF THE OROGENIC BELTS

Map 1.
Illustration 1.

This high has caused the Louann to be thin or absent as well as the corresponding salt controlled structures. This area extends from northeastern Live Oak County to southwestern Colorado County and from Arkansas to Matagorda County along the Gulf of Mexico. The arch separates the Rio Grande salt dome basin and the Texas-Louisiana coastal (Houston Embayment) salt dome basin of which both are depocenters.

The Louann was deposited in the Texas-Louisiana coastal salt dome basin and across the Gulf region salt basins at approximately the same time; that is, as one continuous salt basin. However, the development of the salt domes in the Gulf region did not take place simultaneously.[20] The interior salt domes of east Texas, North Louisiana, and Northern Mississippi developed much earlier than the basinward southern Louisiana and offshore domes.

Andrews described the development of the salt dome basins in three stages.[21] The first stage is the complete deposition of the Louann salt by evaporation. The second stage is divided into two segments. The first segment describes a shore environment with abundant terrigenous sedimentation developing nearshore during Upper Jurassic and Lower Cretaceous time. This area, at present day, is represented by the east Texas and Louisiana-Mississippi Interior basins. Salt domes grew after the Jurassic deposition and again after the Cretaceous deposition. The combined overburden of these two depositional sequences caused the areas to subside. The sequence of Norphelt-Smackover Formations through the Lower Cretaceous Travis Peak Formation was concentrated in the Interior basins area. The facies that developed downdip of these formations were deep water marine shales and ooze. These deposits were of insufficient density to cause subsidence and salt dome growth. Further subsidence of the interior basins was helped by the build up of a bioherm in the shallow offshore waters at the edge of the interior basins.

The second segment of stage two development depicts the depositional center as moving basinward (gulfward). This deposition took place in the mid-Tertiary. The overburden of these sediments again causes salt structures to grow. The pattern of deposition is equivalent to the Mesozoic deposition.

Today's deposition composes the third stage. The depocenter has again moved basinward and has been restricted to a much smaller area. The salt structures here developed much later than the Interior basin domes as they waited for continued accumulation of Tertiary sediments to apply enough pressure on the mother salt bed to create dome structures.

The extension of this model to Mexico, Central America, and Cuba would place these domes' origins as possibly Cretaceous,but more probably Middle Eocene through Recent.

ACTUAL SALT STRUCTURE GROWTH

Salt structures are developed by tectonic forces or by isostatic forces.[22] A combination of the two is possible. The major belief among geologists is that isostatic forces are the predominant producers of salt dome structures.

Halbouty (1910, 1913) and Arrhenius (1912) were early proponents of the isostatic theory.[23] Their work stated the two principal ideas behind isostatic salt flow. One idea is that salt is forced upward from the mother salt bed by the increasing load of overlying sediments that are being deposited. The other notion is that the salt flows up through these overlying sediments because the specific gravity is less than the surrounding sediments.

Barton further elaborated on these two principal ideas.[24] Sediments are laid on top of the mother bed and cause the top of the basement (flat non-domed salt) to subside. The mother bed subsides to this new position. The domal salt core of the bed, because of its lighter specific gravity, (lighter than the surrounding sediments), remains at its original position "floating" in the denser sediments. The overlying sediments cause the mother salt to plastically flow inward, underneath the salt core. This becomes the root of the dome. Meanwhile, the flanks of the mother bed have been pressed down and slightly inward. The inward movement of mother salt to the root of the dome stops when no more mother salt is left (zero thickness) as isostatic equilibrium is met, or as rate of subsidence slows or stops. The structure will continue to flow after deposition ceases, but not towards the dome root.

Nettleton's "fluid mechanical theory" basically agrees with Barton's model.[25] Nettleton emphasizes the upward flow of both the salt and surrounding sediments. They behave as very viscous liquids at depth and then flow very slowly over great lengths of geologic time. The prime reason for sustained flow is the difference in density between salt (specific gravity 2.2) and sediments (specific gravity 1.7-2.0 at surface, but a denser 2.4-2.8 at depth). The lighter salt "floats" through the denser sediments driven by this isostatic disequilibrium force.

Nettleton found the final shape of the dome structure to be determined by the tectonic feature restricting the dome, the thickness of the mother salt, the strength and viscosity of the overlying strata, and the strength or viscosity of the salt itself.[26]

Nettleton perceived a tectonic or orogenic force as the early impetus of salt dome development.[27] An uplift which does not alter the thickness of the salt is favored, and Nettleton believed flow began and continued as deposition continued overhead. The dome then breaks through overlying sediment and actually carries some of these rocks with it as it moves continually upward. The core is now a substantiating upward flow by itself without push from the mother bed as the salt supply from the mother bed has been halted by the formation of the peripheral sink depression. The peripheral sink is formed by the upward moving salt stock's deleting of the mother salt until it is very thin. The depression is filled by the downfaulting of overlying sediments which restricts further flow of supply salt.

Erosion removes the original overlying sediment from above the dome area. The material which the dome was pushing ahead of itself has now been eroded, and groundwater acting on the salt has formed the cap rock. Overlying beds which the dome had forced to overturn now collapse into the dome's peripheral sink as block fault members.

The salt dome described above is known as a shallow "piercement" dome as it rises to a shallow depth, and has "pierced" the overlying strata on its journey upward. Any dome that reaches above a 1000 foot depth is considered to be a shallow dome. Intermediate domes are those which reach a depth of between 1000 and 6000 feet. Deep seated domes are the domes found below a depth of 6000 feet. Nettleton explains the deep seated domes as being salt structures which were separated from the mother bed by competently strong overlying strata.[28] This strata descends through the peripheral sink and merges with the underlying strata to successfully separate the salt dome from the mother bed's supply of salt.

Halbouty and Hardin (1956) do not believe the tectonic or orogenic impetus is necessary to initiate salt dome flow.[29] A sufficient load of overlying sediment is the only force required to start the flow process. The main driving force is the differential between the salt's specific gravity and the surrounding and overlying sediments' specific gravity. The salt's rate of flow is controlled by the amount of sediment deposited over the salt bed flanks as the dome rises through the surrounding sediments through geologic time. The salt stock will slow until the surrounding load becomes thick enough to induce greater compressive force on the flanks of the salt bed, and subsequent accelerated flow rate of the stock due to the regained disequilibirum of densities between the salt and the surrounding sediments. Sediments directly overlying the salt dome are eroded during this stage of slowed movement. The salt dome's top will undergo alteration to cap rock as the stock top is thrust into groundwater near the earth's surface. The stock virtually stops flowing upward at this point due to the obtainment of isostatic equilibrium between the salt and the surrounding near surface strata as their specific gravities are equal or as the surrounding strata's specific gravity is even less than the salt's specific gravity.

The salt dome growth cycle of loading, increased upward flow rate, decreasing upward flow rate, semi-dormancy, and loading continually repeats itself until equilibrium is met. The flow rates of dome structures are also affected by the amount of supply salt from the mother bed, and by restriction by competently strong overlying formations.

The examination of peripheral basin sediments surrounding a piercement dome display a history of the repetitive cycle. The semi-dormant stage is represented by an unconformity due to erosion of the surrounding sediments. These erosional structures must be discerned before faulting can be interpreted in the core section investigations of the area.

The formation of the Gulf region salt domes due to isostasy is the accepted theory of origin among geologists. However, studies of Iranian salt flows show both a tectonic and isostatic origin.[30] The Imam Reza and Sari-i-Naftak diapirs are considered to be originated by a rising anticline. As the folds of this anticline closed with increased tightness the salt was transformed into a sheet-like flow which now appears lying on the surface and flows as a salt glacier.

Other salt structures in Iran are elevated by isostatic forces caused by a sinking syncline descending into the mother salt bed. These salt plateaus have risen above their normally overlying sediments and rest some 1000 feet above them (O'brien, 1957).

The general theory of isostatic growth has been examined by modelling to obtain the parameters at which salt will flow. Halbouty states that Parker and McDowell have done a thorough investigation of initiation of salt flow structures. Halbouty lists four of their initial impeti:[31]

1) Irregularities on the surface of the overburden, either depressions or projections from the general level of the surface.

2) Variations in the thickness of the overburden.

3) Natural variations in the density of the overburden.

4) External stresses producing faults or folds in the overburden which produced varying pressure differentials on the salt equivalent surface.

The first three impeti are those seen in normal isostatic initiation. The first impetus could be applied to the sinking syncline found in Iran as it descends from the surface and applys pressure to the mother salt. The second impetus is the most common initiator of flow and later increases and decreases the rate of flow. Third impetus refers to the restriction and non-restriction of the dome's upward flow. The last impetus results in the tectonic initiation as seen in the Imam Reza and Sari-i-Naftak diapirs which are formed by anticlinal folding.

The overlying sediment load is the main initiator of salt flow. The amount of burial or more precisely the depth at which salt will flow is then an important parameter of flow. Balk (1949) determined that salt will flow due to a shearing stress of 30 kg/cm^3 (427 lbs/in^2).[32] Parker and McDowell determined that this shearing force can be achieved by compressive forces of 853 lbs/in^2. Lower stress strengths could initiate flow if applied over a long enough period of time.

The results of the stress studies found that extremely deep burial was unnecessary for the initiation of salt flow.[33] A sediment load of only 1000 feet could cause salt to flow if the salt bed is of appropriate thickness. McDowell and Parker also found that there was a maximum limit of overburden through which a salt structure could flow. This limit was controlled by the competent strength of the overburden.

An agreement between McDowell and Parker's figure of a required 1000 feet of overburden to induce flow was reached by Trusheim in Germany.[34] He found that 1000 feet of overburden acting on a 300 foot thickness of salt would induce flow within the salt.

Increased depth creates increased temperature, pressure, and strain which effect buried rock bodies.[35] These factors increase the viscosity of rock and the plasticity of salt. A salt body is found to be perfectly plastic at 25,000 feet of burial. The 200^{o}C mark is the minimum temperature for rupture-free flow of a salt body. These conditions are not present, for the most part, throughout the salt basins of the world. Therefore, salt will flow under less than idealistic conditions of viscous flow.

Creep can partly explain the flow of salt under these less than ideal viscous flow conditions.[36] Creep is the movement of a rock body from a higher elevation to a lower elevation due to the effects of gravity. Salt will flow due to creep if the basement, or underlying rock it rests upon, is dipping at an angle of as little as one degree. The result of this flow is a supply of salt to the peripheral sink or a farther inward addition of salt to the rising salt structure.

Salt dome structures not only arise from less than ideal conditions, but also from loading not caused by direct sedimentation overlying the flanks of the dome. The process present in such a situation forms secondary domes concentrically surrounding a master dome.[37]

The master dome develops due to the accepted pattern of loading and growth of any salt structure. The key variable in the development of the secondary domes is the formation of the master dome's peripheral sink (that depression surrounding the dome root where the salt structure has drawn the salt from the mother bed and subsequently "thinned" the salt bed in this area). The subsidence by graben faulting of fringe sediments into the sink itself and the upward growth of the master dome causes disequilibrium between overlying sediments and the surrounding thick salt bordering the peripheral sink. This load disequilibrium causes the growth of the smaller secondary domes.

A good example of the master-secondary dome arrangement is the Spindletop complex in east Texas.[38] The Spindletop dome is considered to be the master dome while anticlines situated in an arc to the east of Spindletop are contributed to secondary deep seated domes, and are associated with normal faulting. The Port Neches dome lying east of Spindletop is thought to be a secondary dome because it approximately lies within the anticlinal arc.

Studies have been made of the genetic relationship among salt structures or groups of salt structures in the Northwest Germany basin originating from the Zechstein salt bed.[39] The old primary dome of initial origin is called the mother dome. This dome triggers the formation of daughter or even third and additional generations of salt structures.

The arrangement of salt domes in this area begins with elongate and meandering salt walls or ridges in the deepest part of the basin. A set of salt domes neighbors these ridges and these in turn are surrounded by salt pillows in the shallower part of the basin. This is similar to the Gulf region arrangement.

One explanation of this salt complex suggests the structures were formed by a rhythmic wave passing through the salt bed.[40] The initiator of the wave is the growth of the primary mother salt stock. The wavefront travels through the salt from the deepest portion to the shallower outer rim of the salt bed. This disturbs the equilibrium of the mother bed, and triggers the formation of the succeeding generations of domes.

A second explanation of the regional salt pattern suggests that the pattern is coordinated to a fault system in the basement strata underlying the salt bed.[41] Trusheim believes the salt begins in a pillow stage (upraised mounds of salt with gently sloping sides and gently curved tops). The salt then flows inward, and steepens the dip of the sides of the pillow until it breaks through the overlying sediment and begins to flow as a diapir.

Salt structures are predominately formed by disequilibrium isostatic forces occurring within the earth's crust, although tectonic compression may have induced salt flow in some of the diapirs of Iran. The salt structure arises from the mother salt bed which was deposited as an evaporite in a barred basin long before the formation of the salt structures.

Sediments are loaded on top of this mother bed over great lengths of geologic time, and compress the salt bed. Shear forces are spawned by these compressive forces and with the help of increased temperature and pressure cause the salt to flow inward to a central core. This core intrudes into the overlying strata as greater loading applys pressure to the flanks of the salt bed, and drives more salt inward to supply the now rising core or dome. The dome now floats upward due to the differences of its own and the surrounding strata's specific gravities. Domes which are able to "pierce" their way through the overlying sediments and reach depths close to the surface are known as shallow "piercement" domes. There are also intermediate piercement domes, and finally deep-seated domes which reached equilibrium with the surrounding strata deeper within the earth. A shallow piercement dome is able to trigger the formation of other peripheral domes by creating additional disequilibrium within the surrounding strata. This is termed by American geologists as the master and secondary dome arrangement.

SHAPE AND COMPOSITION

The top of a salt dome can be circular or elliptical. Circular slopes are common to the United States whereas ellipses are predominant in the Isthmian embayment of Mexico.[42] The top of the dome can range from a half mile to four miles in diameter with the average being two miles in the Gulf area. The salt stock is generally cylindrical, but the flanks may be inclined as well as vertical. The top of the dome may be flat or slightly convex. There are cases of highly irregular to steeply inclined surfaces and generally the top mushrooms and overhangs the cylinder of the salt stock.

The composition of the salt mass itself is a very pure sodium chloride (halite) with minor impurities of calcium sulphate (anhydrite) usually amounting to less than three percent of the stock's composition.[43] Traces of dolomite, calcite, barite, pyrite, quartz, iron minerals, celestite, and sulphur are also present within the halite.

The halite itself is coarsely crystalline with individual crystals ranging in size from a quarter to half an inch in diamter.[44] Layering is commonly seen in the salt stock, and each layer is from one to ten inches in thickness. Interbedding is also present and is characterized by pure white halite and impure gray (anhydrite and dolomite) banding. Evidence of the stress put on the salt stock is represented by the presence of folding (mostly isoclinal) and by the presence of recrystallization.

CAP ROCK

Cap rock is most commonly found in the shallowest piercement domes. However, it has been found as deep as 10,000 feet. The average thickness of cap rock is from 300 to 400 feet with the extreme being about 1000 feet. It is usually thick over the center of the dome, thinning towards the periphery, and thin to absent on the flanks.[45]

Anhydrite is the dominant compound always found in cap rock, and is dissolved directly out of the salt stock. The anhydrite is then altered to (in order of abundance) gypsum, calcite, and sulphur. The structure of cap rock is usually brecciated especially on its upper area. A false cap rock may exist above the true cap rock. This structure is composed of calcareous and siliceous cementations and sometimes of shales which have been carried above the salt dome as it penetrated through the overlying strata.

Normal cap rock can be divided into three mineral differentiated zones:[46] 1) a lower anhydrite zone, 2) middle transitional zone characterized by gypsum, calcite, suphur and sometimes a variable mineralogic suite, and 3) the upper calcite zone. The layers are unequally distributed and highly gradational. The lithology can grade from pure anhydrite to pure gypsum over a few inches or over several feet.

The anhydrite zone is found directly above the salt stock. The anhydrite may extend over the salt stock and travel down the stock as far as 5000 feet. The anhydrite layer makes up the majority of the cap rock and where cap rock is deeply buried anhydrite is usually found alone. This is the original cap rock.

The transition zone is the layer which contains sulphur in either small quantities to terrifically economic reserves, and is an intermediary gradational zone separating the anhydrite and calcite zones. The transition zone is an irregular structure, but is usually thicker near the flanks than in the center of the cap rock.[47]

The transition zone is the scene of active alteration of the anhydrite to gypsum, calcite, and suphur.[48] Alteration begins at the top of the anhydrite zone, and descends down through the anhydrite creating the transition zone. The anhydrite will alter directly to calcite if the anhydrite zone is thick enough and calcite will continue to form as the transition zone develops. The transition zone is also the only zone of alteration where gypsum is produced. The gypsum deposit is formed far more easily than either calcite or sulphur.

Anhydrite alters to gypsum due to hydration of water molecules. The water enters the anhydrite via shear planes and fracture lines. Each individual anhydrite grain is then attacked along its cleavage planes. The result is a gypsum deposit made up of many small interlocking crystals remaining in the outline of the original anhydrite grain.[49] The final gypsum product is made up of large irregularly interlocking crystals as the smaller crystals fuse together.

The alteration of anhydrite to calcite or sulphur may begin before the alteration of anhydrite to gypsum.[50] Usually the calcite and sulphur alteration continues after the gypsum production, but in a few cases the calcite and sulphur alteration has been stopped.

Calcite and sulphur replace the anhydrite and gypsum directly in substantial quantities.[51] Large amounts of both minerals exist in veins and calcite and sulphur will replace anhydrite faster in the absence of gypsum.

Anhydrite forms the initial cap rock with lesser primary crystallizations of dolomite, quartz, calcite, barite, and celestite. These are incorporated into the transition zone with the anhydrite. Calcite and sulphur begin to form along shear zones of the anhydrite and around the dolomite rhombs. Individual grains, and finally the cleavage planes of the anhydrite themselves are attacked. The anhydrite structure is well preserved by the replacement, especially by the sulphur which even retains the anhydrite grains cleavage planes.[52] The replacement of gypsum by calcite and sulphur is slower due to less cleavage planes to attack. The accessory minerals are also replaced by calcite, but only partially by sulphur.

The sulphur and calcite develop together, are closely related, and are of the same age.[53] Sulphur grains are found within calcite, fine calcite crystals within sulphur, and intergrowths between the two in sheer veins off the main sulphur veins.

Disseminated sulphur is found spread throughout the transition zone or immediately above it.[54] Vein calcite and sulphur produced at several different stages are younger than the disseminated sulphur, and are always found associated with disseminated sulphur. Yellow bands of sulphur are produced where veins follow horizontal shear zones. Well developed crystals of both sulphur and calcite occur in cavities and in the partings of shear zones.

The calcite zone lies above the transition zone. It follows the pattern of the transition zone irregularities.[55] It is thicker toward the flanks than at the center of the cap rock. The calcite zone extends down the flanks as far as several thousand feet. It is useful to think of the transition zone as moving down through the anhydrite zone from the calcite zone and leaving alteration products of calcite and sulphur behind.

Calcite occurs throughout the entire extent of the cap rock. All other accessory minerals are associated with the calcite.[56] Calcite and sulphur are again found together in the sulphur-bearing portion of the calcite zone. The replacement again is in the pseudomorph form of the anhydrite grains.

Sulphur is important in the calcite zone especially in the lower part. The upper part of the calcite zone is considered to be "barren cap" where any sulphur has been replaced by calcite and pyrite.[57]

The cap rock is created by undersaturated groundwater dissolving and altering the salt itself. Any dome which does not reach shallow enough depth to be attacked by circulating groundwater will have no cap rock. Salt domes which have only recently been thrusted into the groundwater zone will have no cap rock or only a thin or patchy layer of cap rock composed only of residual anhydrite.

The dome is attacked most vigorously at its apex.[58] Cementation of surrounding sediments takes place at this early stage and begins to form the false cap rock. Anhydrite is being dissolved out of the halite and is settling in pockets and solution cavities in the salt surface to form an anhydrite sand consisting of individual grains of the mineral of exact composition as seen in the host halite. Waters also attack the sides of the stock, and anhydrite also begins to accumulate on these flanks.

The top of the salt dome is leveled off, and a flat surface is formed where anhydrite sand accumulates in greater volume.[58] The false cap rock protects it from contamination and the anhydrite remains pure except for the other insolubles (dolomite, pyrite, etc.) being dissolved out of the salt stock itself.

The cap rock shrinks in size and tightens vertically due to the partial collapse of the false cap rock and the continued upthrust of the salt dome. Anhydrite precipitates from the sulphurous brine and individual grains begin to coalesce to form a matty residue.

Salt continues to be removed by erosive action of the groundwater, but new salt to be attacked is provided by the continued upthrust of the salt plug. Sedimentation continues above the salt plug, and is compensated for by the upthrusting. The anhydrite becomes brecciated by the upthrusting of the dome and collapse of the false cap rock and of the newly formed true cap rock. Anhydrite on both the top and the flanks of the dome is broken and recemented repeatedly during this phase of alteration.[59]

A marked difference is now perceived in the formation of cap rock. The anhydrite begins to be altered itself. This is the beginning of the transition zone. The anhydrite alters first to gypsum (hydrous $CaSO_4$), and both subsequently alter to calcite and finally to sulphur. A pseudomorph of the anhydrite gypsum crystalline structure is retained by the calcite and sulphur. At this time gypsum might be the only alteration product formed solely by hydration.[60] A thin or thick layer of anhydrite might be present when the transition zone begins its formation.

The transition zone continues its formation moving downward through the anhydrite. The anhydrite is reduced to H_2S gas which in turn may be oxidized to sulphur. Calcite is also continually formed from calcium cations liberated from the anhydrite and from CO_3 anions present in the groundwater. A thick accumulation of this calcite forms the calcite zone above the transition zone (actually replacing the transition zone in this area). The upper part of this zone sees the formation of secondary veins of calcite, sulphur, sulphides, barite and celestite.[61] The last three compounds will also replace sulphur in the transition zone. Hydrocarbons which enter in with the groundwaters reduce the sulphur and redeposit it in another oxidizing environment in the cap rock or it may escape. The groundwater continues to circulate in the upper calcite zone dissolving out pockets and caverns. Removal of sulphur may form additional cavities, and any remaining salt is dissolved out causes collapse of the lower part of the zone.[62] Salt domes at this stage have either commercial deposits of sulphur or thick barren calcite zones devoid of sulphur.

The salt dome now slows its entrance into the circulating groundwater region. A cementation seal is formed around the cap rock effectively blocking or retarding the entrance of fresh groundwater. The cap rock's growth is essentially ended at this point. Sulphur producing salt domes are examplative of this phase of development.

The cap rock in its final stage begins to be destroyed. It may be eroded if uplifted to the surface or shattered by sudden uplift of the dome if it is a thin cap.[63] A sudden uplift by the salt dome may also maroon a thick cap rock at a lower level below the surface.

The thickness of cap rock is therefore dependent on accumulation conditions, total amount of salt dissolved, and the amount of anhydrite and other mineral residue in the salt. The complete absence of salt is due to unfavorable accumulation conditions or because the salt stock has been so recently upthrust into the groundwater area that the groundwater has had insufficient time to alter the stock head.

The transition zone appears only after a substantial thickness of anhydrite has been formed. Altering solutions enter from the flanks or laterally and are petroleum and hydrogen sulphide laden.[64] The altering of the anhydrite occurs by reduction followed by oxidation.

An abionic description of the reactions in the transition zone which produce native sulphur begin with the reduction of anhydrite in excess of hydrogen sulphide which creates calcium sulphide. This calcium sulphide is quickly reduced to hydrogen sulphide which in turn is immediately oxidized to sulphur or migrates to an oxidizing environment within the cap rock and is then oxidized.[65] Calcite is formed by the reaction of the hydrolyzed reduction by-product calcium hydroxide with dissolved carbon dioxide existing as carbonic acid in groundwater. This process is represented by the chemical equations:

$$CaS + 2H_2O \rightarrow Ca(OH)_2 + H_2S$$

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O$$

A biogenic description of these same reactions which is highly believed by scientists begins with the reduction of anhydrite by the anaerobic bacteria named Desulfovibrio. Utilizing organic carbon from: 1) nearby petroleum deposits, 2) the hydrocarbons in the groundwater or, 3) a preceeding heterotrophic bacteria which could better metabolize hydrocarbon[65] as reducing power, the anhydrite is broken down to carbon dioxide and calcium sulphide. These products lead to the formation of calcite and hydrogen sulphide. The hydrogen sulphide is then oxidized at the site or again migrates to a more beneficial oxidizing environment in the cap rock and is oxidized to native sulphur. The processes are described by these equations:

$$CaSO_4 + 2Corg \xrightarrow[\text{reducers}]{\text{sulfate}} 2CO_2 + CaS$$

$$CaS + CO_2 + H_2O \rightarrow CaCO_3 + H_2S$$

$$H_2S + \tfrac{1}{2}O_2 \rightarrow S^o + H_2O$$

Cap rock deposits of sulphur and calcite are considered to be epigenetic.[66] This means they are developed in preformed host rock which are normally associated with terrestrial environments. The process of sulphate reduction by the Desulfovibrio is known as dissimilatory sulphate reduction.[67] It is most commonly associated with the respiration of marine anaerobic bacteria. The sulphate itself is known as the bacteria's terminal electron receptor[68] which combines with the one-celled biotum's biochemicals to give the organism energy to function and reproduce.

Sulphate reducers, e.g. Desulfovibrio, perform sulphur isotope fractionalization because the bacteria can discern the difference between ^{32}S and ^{34}S isotopes of sulphur.[69] The ^{32}S isotope usually composes 95.1% of all compounds while ^{34}S isotope composes about 4.2% of all sulphur compounds. The $^{32}S/^{34}S$ ratio of natural sulphur compound is between 21.3 and 23.2. Meteoritic sulphur has a $^{32}S/^{34}S$ ratio of 22.22. This meteoritic ratio, because of its uniformity between samples, is used as a reference standard to compare other ratios of sulphur compounds.

$$\delta^{34}S = \frac{^{34}S/^{32}S \text{ sample} - {}^{34}S/^{32}S \text{ meteoritic or standard}}{^{34}S/^{32}S \text{ meteoritic or standard}}$$

The comparison of sulphur compounds found in nature to the standard helps to differentiate between biogenically and abiogenically formed sulphur compounds. Abiogenic $\delta^{34}S$ values generally fall within a narrow range with a positive sign while biogenic $\delta^{34}S$ values fall within a wide range and have a negative sign.

Feely and Kulp (1957) have applied this ratio in a number of intriguing ways to the salt dome, its cap rock, and to sulphur generation. They determined that a single evaporative sequence (e.g. the Louann salt) was responsible for all of the salt domes in the Gulf Coast area by utilizing the $^{32}S/^{34}S$ ratio of sulphate found in the salt of the anhydrite.[70]

The $^{32}S/^{34}S$ ratio of sulphate present in the halite stock and the anhydrite cap rock substantiates the theory of origin of cap rock from the residue in the salt.[71]

Evidence to support the biogenic generation of cap rock sulphur has a beginning as based on the length of time it would take petroleum to reduce sulphate versus Desulfovibrio to complete the same process. Petroleum reduction would involve about 150 million years while Desulfovibrio reduction would involve less than a million years. The petroleum time is almost as old in inception as the Louann salt is in its deposition whereas the Desulfovibrio reduction time span is much closer to the length of time salt domes have been present and exposed to groundwater.

Desulfovibrio causes fractionalization of sulphur isotopes during reduction of sulphate.[72] The bacteria's slow growth enriches hydrogen sulphide by at least 2.7% over the initial sulphur -32 content of original sulphate. Domes with immature cap rock show a correspondingly lower enrichment level (e.g. 1.2% at Spindletop) compared to domes with mature cap rock (e.g. 3.8% at Moss Bluff). This is further evidence for the belief in the "sulphate reduction performed by Desulfovibrio theory" as similarly seen in the enrichment of calcite cap rock. A varied $^{32}S/^{34}S$ ratio in the calcite cap rock eludes to an envrionment of separated, small scale biochemical interactions. This is consistent with anaerobic bacteria's widely varied $\delta^{34}S$ values.[73]

The isotopic composition of the native sulphur in cap rock is heavier than related hydrogen sulphide and lighter than associated sulphate which verifies its production by sulphate -H_2S reaction (this is the standard model where native sulphur attains more ^{34}S than ^{32}S isotope).[74]

Two interesting points about calcite cap rock involve its composition and thickness. Calcite of salt dome cap rock can be differentiated from that of conventional sedimentary lime by its $^{13}C/^{12}C$ ratio which, for the cap rock lime, is closer to a petroleum ratio than to that of a normal lime ratio.[75] The second point is that a thick calcite cap rock illustrates the image of the dome at some point intruded through a petroliferous horizon very close (about a mile) beneath the surface.[76]

Finally, isotopic composition is uniform for cap rock sulphur pointing to considerable isotopic exchange and supporting the theory of fractionalization of sulphur by bacteria instead of chemical formation.

The collective proof strongly favors biogenic emplacement of sulphur within the cap rock. Economically exploitable caprock will be that which is highly matured and contains thickened transition and calcite zones, where anhydrite has been highly reduced by Desulfovibrio and effectively trapped within the cap rock as sulphur.

SULPHUR

Sulphur is the eighteenth most abundant mineral in the earth's crust. It occurs 1) in its pure uncombined form which is known as native sulphur or brimstone, 2) in combination with metallic elements to form sulphides (e.g. pyrite FeS_2) or sulfosalts (e.g. tetrahedrite $Cu_{12}Sb_4S_{13}$) and 3) combined with oxygen to form the sulphate $(SO_4)^{-2}$ anion which then singly bonds with a variety of large divalent cations to form sulphates (e.g. anhydrite $CaSO_4$).

Native sulphur is found 1) around and inside the craters and fumaroles of volcanoes, 2) as encrustations at the edges of hot sulphur springs and 3) embedded in limestone as in the cap rock of salt domes.

Sulphur has been part of man's culture since ancient times. The witch doctors of primitive tribes used sulphur to drive away evil spirits with its thick and irritating smoke. The tribes also used sulphur to kill insects and to bleach their feathers, furs, and wool. The Greeks used it in killing insects and to dispel illness from homes. The Egyptians made medicinal salves out of brimstone. Pliny described sulphur in his Natural History and talks of its mining, refinement, and use in art and industry. The Romans used sulphur in its traditional ways and devised the first incendiary bombs made of rosin, bitumen, and sulphur. The Chinese developed gunpowder in 1200 A.D.

by mixing 70-75% saltpeter ($NaNO_3$), 14-16% charcoal, and 10-15% sulphur. Gunpowder was a key to ending the Feudal System of Europe, and remained the only explosive compound until after the Boer War in the early 1900's.[77]

The advent of sulphuric acid was the beginning of the great demand for sulphur. Oil of vitriol was first created by heating $FeSO_4$ or pyrite under a glass bell and passing the fumes through water. This process was soon followed by Johann Glauber, an alchemist who added niter-nitrate to brimstone and placed the mixture under a glass bell. This created SO_3 instead of SO_2 and by putting these fumes through water obtained: $SO_3 + H_2O \rightarrow H_2SO_4$, sulphuric acid.[78]

Sulphuric acid was and is the mainstay of the chemical industry.[79] Innovation in the manufacture of sulphuric acid and in the chemical industry for the consumption of sulphuric acid have led to the sulphuric acid industry's growth and subsequently to the sulphur industry's expansion.

Innovations in the manufacture of sulphuric acid include: 1) the lead chamber - John Roebuck, M.D., inventor Britain - it replaced the glass bell - and in so doing increased the quantity of acid produced a hundred fold as the number and size of the chambers grew; 2) the Peraett furnace - 1833 - SO_2 obtained from roasting pyrites good for the pyrite industry but not native sulphur, the disadvantages of this process are the impurities it produces in the acid, handling and labor costs, and fly ash pollution, 3) ultra strength H_2SO_4 produced by Nordhausen, Bohemia by fuming acid oleum from ferrous sulphate, and 4) the contact method where SO_2 is converted to SO_3 directly by means of a catalyst and uses brimstone as raw material the acid produced is pure, strong, less labor is needed and handling is cheaper. No fly ash is produced.

The development of demand of sulphuric acid and of sulphur directly include: 1) Leblanc Process Soda Alkali business to produce $NaCO_3$ (soda-ash) for industrial manufacturing, the acid is used to decompose NaCl, 2) 1873 - lime - sulphite paper pulp process developed by Swedish chemist C. D. Ekmann - uses sulphur directly, 3) sulphur being used in vulcanization of rubber to make it more resistant to water, resiliant, temperature independent, weather independent, elastic,[80] 4) Liebig's research into plant foods spawned the fertilizer industry - sulphuric acid used to make super-phosphates by treating phosphate rock - fertilizer is still the main consumer of sulphuric acid today - and main impetus behind sulphuric acid sulphur industry growth, 5) production of kerosene after the Civil War spawned the use of sulphuric acid in petroleum refinement and, 6) the development of synthetic fibers uses sulphuric acid. A more complete list of industries and products consuming sulphur today are:

acids
alcohols
alum
ammonium sulphate
aniline
bleaching agent
bromine
carbon dioxide
carbon disulphide
carbon tetrachloride
casein
cellphane
celluloid
cellulose esters
cements
chlorine
coke
copper
dehydrating agent
detergents
dyes
ebonite
electroplating
explosives
fertilizers
fire extinguishers
fireproofing agents
fireworks
food preservatives
fumigants
fungicides
glue
glycerin
impregnant
inorganic or organic acids
insecticides
leather
livestock food
lubricants
magnesium
matches
medicine
metallurogy
paints and pigments
paper pulp
petroleum products
pharmaceuticals
phenol
photography
plastics
plate glass
rayon
refrigerants
resins
road-surfacing materials
rubber goods
soap
soada
solvents
steel pickling and galvanizing
storage batteries
sugar
sulphonated oils
synthetic fibers
synthetic rubber
textiles
tires, rubber
water purification
and more

The sulphur to supply these industries comes from both elemental (uncombined with any other element in molecular structure) and nonelemental (combined with another element in molecular structure and used in non-separated form) sources. Elemental production includes: 1) the Frasch hot water mining process performed on the cap rock of salt domes in the Gulf of Mexico region and Poland, 2) conventional mining of sedimental and surface deposits such as the Sicilian deposits (the original world source of modern sulphur), west Texas, and western United States, 3) separated from metal in metallic sulphides, e.g. pyrites for roasting of which the Spanish pyrites are the most famous, and 4) the refinement of H_2S gas involved in "sweetening" sour natural gas which made Canada the largest producer of sulphur in the world. Non-elemental sources are: 1) H_2S from oil refining and smelting operations, 2) by-product acid from copper and zinc smelters ("sludge acid"), and, 3) gypsum and anhydrite deposits some of which are most favorably represented in the southwest and west of the United States.

Canada is the main producer of sulphur today due to the enormous sour gas fields of Alberta. However, until the advent of the refinement of H_2S to sulphur from these sour gas fields arose in the 1950's, the dominant supplier and price leader in the world were the sulphur companies of the Gulf of Mexico region. This role was provided for them by the sulphur deposits found in the cap rock of salt domes. The mining of these deposits was and is facilitated by the Frasch hot water mining method.

FRASCH AND THE FRASCH HOT WATER MINING METHOD

Hermann Frasch was born in Würtenburg, Germany on Christmas Day of 1851.[81] He migrated to the United States in 1870 and became a lab assistant to Professor John M. Maisch in the Philadelphia College of Pharmacy.

Frasch devoted himself to the science of chemistry and particularly to the applications of the science to the newly found and greatly expanding petroleum industry.

Frasch improved the process for refining paraffin wax in 1876. He sold the patent to the Standard Oil Company.[82] John D. Rockefeller was so impressed with Frasch that he asked him to move to Cleveland and become a consulting chemist specializing in petroleum and its products. He grew wealthy as a consultant through his expertise in petroleum chemistry.

Frasch acquired the Empire Oil Company, its wells, and small refinery near Petrolia, Ontario in 1885.[83] The site was producing sour crude which produced a high sulphur kerosene of poor quality used in lamp lighting. Frasch made the kerosene profitable by devising a desulphurization process for his crude.

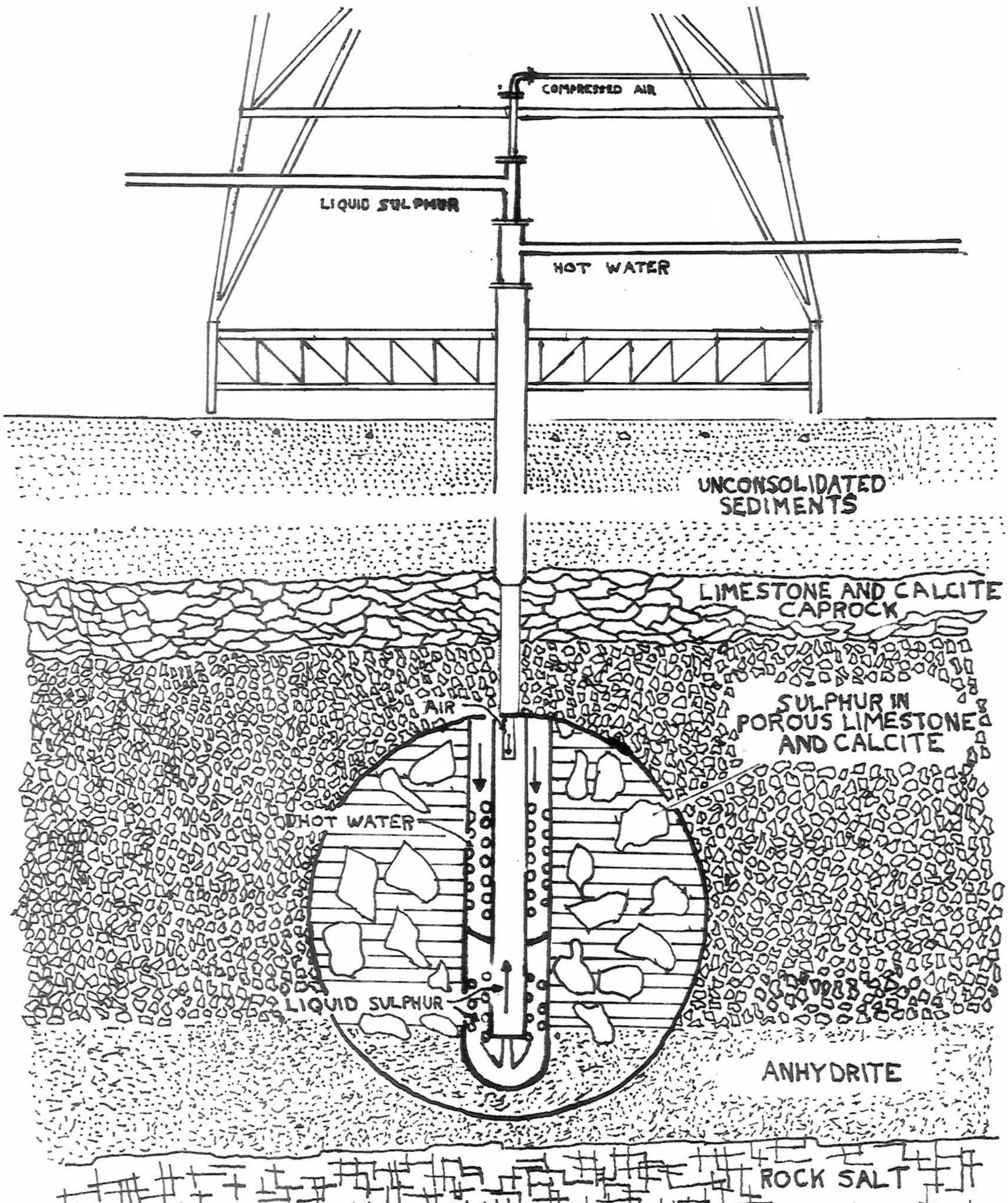
Rockefeller at the same time was discovering sour crudes in Ohio. He heard Frasch's successful desulphurization process and bought the patents and company outright.[84]

Frasch then became the first director of research for the Standard Oil Company. Good salary and royalties on all future inventions in the petroleum industry were part of his contract. He was also given two months of free time, the majority of which he spent working on his own inventions. His patents and Empire Oil Company had been purchased with Standard Oil Stock. The desulphurization of sour crudes made the Standard Oil Company huge profits, and the stock rose to $820/share.[85] Frasch sold half of his stock and became extremely wealthy while retaining his job with Standard Oil.

Besides the contributions to the early oil refining techniques, Frasch invented on his own time[86] a recovery process for tin scrap, manufacture of white lead from Galena, manufacture of elements in thermal-electrical generators, paraffin wax paper, electric light carbons, produced sodium carbonate from salt, first to think of treating old oil wells with hydrochloric acid for extended production, and the Frasch hot water mining process. He held 64 United States patents in all, most of which were huge commercial successes involving industry on a large scale.[87] He increased the obtainment of oil and sulphur a thousand-fold before his death on May 1, 1914.

Frasch's process is based on the fact that sulphur melts at about 116°C. The well is drilled by a rotary rig similar to those utilized by the petroleum industry.[88] The well contains an arrangement of pipes fitted one inside another. There are usually four in today's wells though three can be used. The outermost pipe is either eight or ten inches in diameter. This pipe is set in the top of the cap rock and prevents the sides from caving in. A six inch pipe is fitted through this outermost pipe and extends through the sulphur formation and is set in the top of the underlying anhydrite or gypsum layer.[89] A three inch pipe is lowered through the six inch pipe and rests on a collar near the bottom of the sulphur-bearing rock. The annular space between the two pipes is sealed by this collar. A one-inch air pipe runs down the center of the arrangement and is located just above the collar. The six inch pipe is perforated at two levels separated by the collar. Hot water is ejected out the top set of holes while the liquified sulphur enters through the lower set of holes.

The well is now steamed.[90] The water, before injection, is treated to destroy any salts which would form scales or corrosives that would damage the pipe. The water is heated to a temperature range between 320°-



UNDERGROUND PIPING ARRANGEMENT
FOR FRASCH MINING

Illustration 2

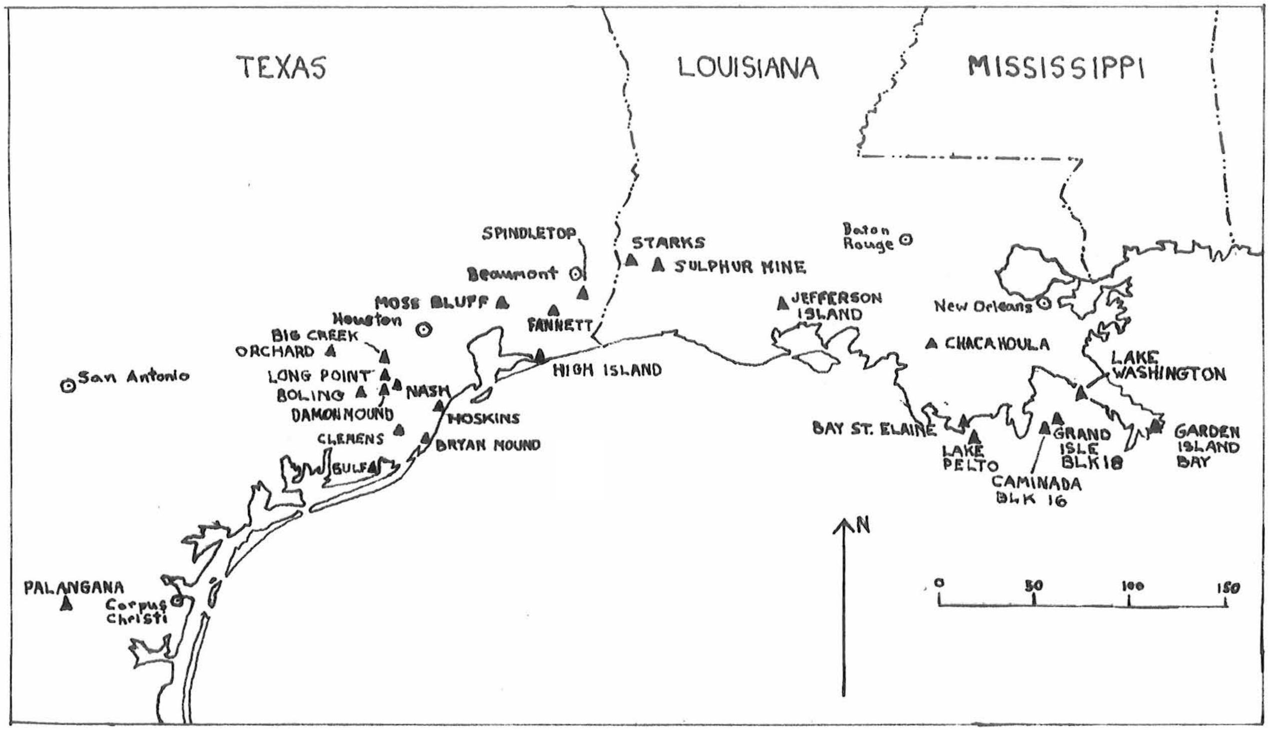
340^{0}F. The water is then pumped under pressure of about 100-250 lb per in^2, and down through the annular space between the six inch and three inch pipe until it reaches the higher set of perforations in the six inch pipe, and flows out into the sulphur bearing formation. This area is raised well beyond the sulphur's melting point.[91]

The heated zone takes the shape of an inverted cone where the outer limits remain below the fusion point of sulphur, and the apex is at the bottom of the hole. The molten sulphur runs in the dome, and being heavier than water, sinks into a pool at the bottom of the well. The pressure within the dome forces the sulphur part way up the three inch pipe. Compressed air at 500 lb/in^2 is forced down the one inch pipe into the sulphur pool changing the specific gravity of the sulphur-water solution so it flows up the three inch pipe, and is discharged into steam heated tanks where it is metered and the air is removed. The liquid sulphur is then transferred to vats to be stored as either a liquid or a solid.[92]

DEVELOPMENT OF THE FRASCH INDUSTRY

The first Frasch mining operation was located in Calcasieu Parish in southwest Louisiana; thirty-five miles north of the Gulf of Mexico and twenty miles east of the Texas border. The property consisted of a fifty-five acre mound of land gently rising from the surrounding swampland.

The land was first investigated for oil because of conspicuous oil seepage observed at the surface. Drilling provided only small shows of oil, and the land was returned to its original owner for the development of sulphur production. Attempts were made to mine the dome by conventional shaft mining techniques. Forty years transpired in which all attempts at direct sulphur mining failed.



SULPHUR BEARING SALT DOMES OF THE LOUISIANA AND TEXAS GULF AREA

Map 2.
Illustration 3.

The last attempt at conventional mining left the property in the hands of the American Sulphur Company. Frasch and the American Sulphur Company negotiated an agreement whereupon costs and profits would be shared fifty-fifty upon the production of a sizable amount of sulphur which would prove Frasch's process as commercially feasible.

Frasch's initial well consisted of a ten-inch casing set in the cap rock above the sulphur. An eight-inch borehole extended byond this casing, and through the sulphur bearing zone to its bottom. This borehole was fitted with a six-inch pipe perforated near its bottom to allow the influx of melted sulphur. A top set of perforations were separated from the lower set by an iron ring inside the pipe which could accept a two and a half inch nipple. These larger perforations allowed the hot water to flow out of the pipe. The final section of pipe was three inches in diameter and was set on the iron ring inside the six-inch casing.

The original well was equipped with a conventional sucker rod which was placed inside the three-inch pipe at about 175 feet. The sulphur deposit itself was located at about 623 feet. The water supplied by the surrounding swamp was super heated by steam provided by four one-hundred horse power boilers to a cylindrical steel heater, twenty feet high and thirty inches in diameter. The heater consisted of a set of staggered cast iron pans which thoroughly heated the water.[93] The water was then gravity fed to the well-head.

The well was steamed on Christmas Eve 1894 and twenty-four hours later produced sulphur to the jubiliation of Frasch and the twelve members of his crew. So much sulphur was extracted by the well that a pit was quickly dug adjacent to the drilling rig and lined with wooden planks. This was the first sulphur containment vat.

The pump began to fail after four hours of pumping, and on inspection of the steel sucker-rod it was found to have corroded away to almost nothing. Frasch returned to Cleveland to obtain a set of aluminum sucker-rods. Soon after he left, one of the boilers nearly exploded. The operation was quickly shut down, and the liquid sulphur solidified in the three-inch pipe due to the extended period of non-steaming. The crew was forced to tediously chip the sulphur away from the pipe in order to clear the pipe and raise it to the surface. This task was not completed until late fall. The well was then steamed again, and using the aluminum sucker-rods produced five hundred tons of sulphur. Finally, the aluminum sucker-rod snapped, temporarily halting the operation.

Frasch observed, due to the boiler accident, that millions of gallons of water would be needed for a successful commerical operation.[94] He instructed his superintendent of field operations, Jacob C. Hoffman, to dig an eight-mile canal to the Houston River to obtain this plentiful supply of water. Four new 150 horsepower boilers were also to be delivered.

Frasch next went to New York to renegotiate with Hewitt and Cooper of the American Sulphur Company. They agreed that five hundred tons of sulphur proved the Frasch process a success. This led to the incorporation of the Union Sulphur Company in the state of New Jersey on Janaury 23, 1896.[95] The company obtained all property and mineral rights at the location, now named Sulphur Mine, and also the Frasch patents. The company was divided equally between the shareholders of the American Sulphur Company and Frasch, Squire (the secretary of Standard Oil) and Frank Rockefeller.[96]

Frasch returned to Cleveland to work out the problems of raising the sulphur to the surface. He realized the sucker-rod failure would be a constant problem to a commercial venture. He knew that liquid sulphur has a density of 1.811 grams per cubic centimeter. Frasch concluded that pumping compressed air into the liquid sulphur and filling it with air bubbles would sufficiently reduce the sulphur's density below the surrounding groundwater outside the three-inch pipe. The greater hydrostatic pressure on the outside of the pipe would force the column of sulphur to the surface. The air would be delivered to the sulphur column at a depth of from fifty to one hundred feet by being forced down the center of the three-inch pipe. A constant level of sulphur must also stand in the pipe at all times for this process to work efficiently. A continuous supply of liquid sulphur was required to maintain this level.

Frasch also knew that the temperature inside the cap rock must be carefully controlled to maintain a continuous supply of sulphur at the bottom of the well. Sulphur melts at approximately 114^{o}C and becomes a thin and runny yellow liquid. The liquid becomes thick and brown at 150^{o}C and is too viscous for pumping at this temperature, and at 220^{o}C the sulphur becomes almost plastic and is far too viscous to be pumped to the surface.[97]

The temperature must first be controlled by pumping the correct amount of water at the right temperature into the cap rock. The thermal conductivity of the cap rock is important in effecting the temperature within the cap rock. Frasch found that a fissurous and cavernous cap rock would allow the hot water to flow randomly through the cap rock, and away from the well causing inefficient production of sulphur. Frasch's solution to this problem was the pumping of mud down the well to fill these cavities. The other factor affecting thermal efficiency was the over abundant quantity of cold water inside the cap rock which would dillute the heating efficiency of the hot water. Frasch devised a method of drilling bleed wells adjacent to the production wells to drain off this cold water.[98]

Frasch also set up his new wells to deliver water to both the bottom and top of the sulphur deposit by pumping hot water down both the ten-inch and six-inch pipes. This also increased the speed at which the sulphur melted.

This double discharge system provided thorough heating of the sulphur deposit.[99] Hot water provided only at the top of the deposit will float on top of any cold water present in the cap rock. The melted sulphur will sink down through the cold water as it is heavier than the water, and solidify as it passes through this cold water. Hot water discharged at the bottom of the sulphur deposit will rise through the cold water, lose its heat, and subsequently lose its heating capacity. The double discharge system eliminates both of these disadvantages.

Frasch also took measures to insure the non-solidification of sulphur in the production pipe if the well again had to be "cooled". He first shortened the bottom strainer to prevent a freeze in the sulphur line. He then devised a system to pull the six-inch pipe well up into the derrick while hot water was still being pumped down the well to keep the sulphur in the pipe melted even as it reached the surface.

The Sulphur Mine operation, in total, was unprofitable for the early part of its operation due to irregular production and the high cost of fuel. The operation was actually forced to shut down for a short period as Frasch searched for additional funds. He received these funds from Hewitt and Cooper after considerable stalling from both men. Three additional wells were drilled by January 10, 1901, but produced only 3114 tons of sulphur.

The whole operation was saved by the discovery of great quantities of oil at the Spindletop dome in east Texas only sixty miles west of Sulphur Mine. This fuel oil replaced the expensive Alabama coal which Frasch had been forced to use up until this time. The fuel oil only cost 60¢ a barrel on delivery to

Sulphur Mine, and through the utilization of this cheap energy source production rose from 3078 long tons in 1901 to 218,950 tons in 1905 with an increase from two wells to nineteen wells.

The Sicilian sulphur industry was Frasch's only direct competition during this period of production, and up until the advent of the Union Sulphur Company it was the sole possessor of the native sulphur market. They had for years been plagued by mismanagement and high Italian and local taxes. However, at this time the industry had been stabilized by a group of British alkali manufacturers.

The Anglo-Sicilian cooperative undercut Union Sulphur prices in the United States by selling their sulphur just above cost. Frasch felt threatened by this activity, and clearly stated he intended to keep the American market. They continued to ignore Frasch, so he invaded the European market. He successfully won a considerable part of the market away from the Anglo-Sicilian company.[100] The final product of the Frasch invasion was the dissolution of the Anglo-Sicilian company.

The withdrawal of the English, and declining sales spawned mass unemployment throughout the Sicilian sulphur industry. This led to rioting by the unemployed workers. The Italian government was forced to nationalize the industry in order to stabilize the industry once again. This was done by the formation of the Compulsory Consortium for the Sicilian Sulphur Industry,[101] and the nationalization of the Sicilian industry was the first attempt by any nation to valorize a domestic commodity on a world level.

The Italian management of the Sicilian industry was far from perfect. The government set up a poor system of issuing warrants to producers for their deliveries of sulphur. Many times there were no buyers for the sulphur or the price of the warrants would not be matched by the buyers. Meanwhile, the producers would cash their high value warrants at Italian banks; robbing the government of revenue. The government reduced the warrant value to a low amount which caused hardship for the producers. At best this method of financial transaction was a temporary cure for the Sicilian industry. The single real positive aspect of the nationalization was that the Italians now could negotiate on a one to one basis with the Union Sulphur Company.[102]

The two factions battled with each other until 1908 when an agreement was struck, dividing the world market into thirds. The Italians were to receive 2/3 of the market while the American company was to receive 1/3 of the market. The United States market was excluded from this world market and tacitly left in the hands of the Americans. The agreement was to last till the Consortium's dissolution in 1918. Prices were set at $22 a long ton upon delivery, and $18 domestically. All went well until 1912.

Woodrow Wilson then passed the famous "Five Sisters Act" in which one clause disallowed a New Jersey company to hold any legal contracts with a foreign country. Frasch was forced to break his agreement with the Italian government. The two industries were again on their own.

The Union Sulphur Company increased its production from 220,000 long tons in 1905 to a total of 787,735 long tons in 1912.[103] Frasch marketed his sulphur to all buyers for the same constant and open price. He kept the price reasonable, and was always looking for new markets applicable to sulphur and aided in research in inventing new sulphur using processes. The Sicilians were often cheaper, but their delivery was sporadic and many times short as no guarantees on weights were made by the Italian government. These practices made Frasch's sulphur a good buy.

While the Union Sulphur Company was busily competing with the Sicilian industry for the world sulphur trade, a new company was developing in east Texas. The location was at the mouth of the Brazos River flowing into the Gulf of Mexico. The mound had first been investigated for oil by the famous Colonel Lucas in 1901. He abandoned the project because of excess H_2S gas and dry holes.

Henry Straiti appeared in 1906, and finding sulphur in test wells, enlisted the aid of a Houston financier named George Hamman. Hamman in turn sought out Edward F. Simms who convinced the Texas Company to invest $100,000 in exploration of Bryanmound. Sulphur was found, but no oil and the Texas Company withdrew from the venture. Hamman and Simms then formed the Gulf Development Company and bought more leases in 1908. They continued their drilling and completed twenty-seven test wells all showing sulphur and proving 300 acres of the mound. This convinced Hamman and Simms, who picked up the purchase options on the rest of the Bryanmound area.

More investors were attracted to Bryanmound because of the success seen at Sulphur Mine. The most influential of these investors in the formulation of the Freeport Sulphur Company, and the development of Bryanmound was Erick P. Swenson, a Texas turned New York City financier. Swenson was instrumental in obtaining more investors for the Bryanmound project. The Vanderlip-Swenson-Tilghman Syndicate was formed, and negotiated the formulation of a new sulphur company with Simms and Hamman. The Freeport Sulphur Company was incorporated in Texas on July 12, 1912.[104]

The Freeport company obtained all the sulphur property, and also won a court battle with the Union Sulphur Company over infringement of patent rights. The Freeport Townsite Company also came into being to build a city on the west side of the Brazos (this city was also the brainchild of Eric P. Swenson). The Freeport Sulphur Company was to have an operating sulphur extraction plant by June 1, 1913.

The construction of the sulphur operation, and the town of Freeport developed quickly, despite transportation and labor obstacles. Three wells were drilled while construction took place, all of which produced quantities of hydrogen sulphide gas sometimes blowing craters in the mound and destroying the drilling. However, on November 12, 1912 the work was finished and using the Frasch process sulphur was flowing by 5:00 p.m., and presented Texas with its first production of sulphur.

The Big Hill salt dome in Matagorda County was the next sulphur laden dome to be brought into production. The mound here is 4000 feet long and 2400 feet wide and only twenty feet above the marsh surface. The mound was first explored for oil, and modestly produced oil for a short period of time in 1904. Salt water soon appeared in all existing wells, and production fell off to 400 barrels a day forcing the exodus of all oil men by 1905.

A group of St. Louisian men spurred the exploration of the dome for sulphur interested by the shows reported by oil drillers. They organized the Gulf Sulphur Company with several Texas associates, and began further exploratory drilling. The St. Louis men found a sulphur operation to be a costlier venture than they planned, and were glad to have an associate of the Bryanmound developers, Spencer C. Browne, examine their property in the hope of obtaining additional funds from the Bryanmound-New York backers.

Browne reported to his associates that Big Hill was as promising a find as Bryanmound. Two of these associates, Seeley W. Mudd and Bernard Baruch went east and convinced J. P. Morgan to invest in Big Hill.

The Gulf Sulphur Company now came under control of Baruch and Mudd. Mudd was elected president and purchased the dome area. The development of the mound's sulphur potentials was put in the hands of W. T. Lundy, a young consulting engineer from San Francisco.

However, the development of the Big Hill mound was delayed by the first World War. The government needed a large supply of sulphur for the production of sulphuric acid for use in the manufacture of munitions. Unfortunately, contracts to industry were only awarded to those who could guarantee delivery of their product. The investors were unagreeable to guarantee the delivery of sulphur to the government from their unproven dome.

The war was a boon to both the Freeport and Union Sulphur Companies. The demand called for full and unlimited production by both companies.[105] The munitions industry demanded pure and high strength sulphuric acid which could only be produced by the contact method utilizing native sulphur and not pyrites.

The statistical breakdown of the two American companies at the beginning of the war was as follows:[106]

combined stocks	1,440,000 tons
year's projected production	1,400,000 tons
Freeport	500,000 tons
Union	900,000 tons
holes drilled	
Freeport	124
Union	600
Reserves	
Bryanmound	2,675,000 tons
Sulphur Mine	4,706,000 tons
Total	7,281,000 long tons
Production Facilities	
Freeport	3 power plants
power rating	23,800 hp
heating capacity	8,000,000 gallons of water
boilers are operated at 150-175% of their rating 24 hours a day and steam six wells	
daily production:	1,500 tons

Union	8 power plants
power rating	21,480 hp
	6 power plants
power rating	16,230 hp
boilers are operated at 150% of their rating 24 hours a day and steam seven wells	
daily production:	2,500 tons

Each company burned approximately 4,000 barrels of fuel a day. Freeport purchased oil from Mexico while Union purchased Mexican, Louisiana, and Texas oil.

The only major production problem which developed during this wartime period was the three week shutdown of the Sulphur Mine operation due to its destruction caused by a cyclone. Stockpiles filled the gap of this lost production, but the margin of safety was cut to a dangerous level. The government at this time looked for the Big Hill operation to fill the gap of needed sulphur.

Construction of Big Hill began August 13, 1918 and was completed on March 15, 1919 when production began.[107] This was four months after the end of World War I. The site became known as the Gulf location and was extremely successful due to a tight formation of unconsolidated sediments overlying the cap rock. This formation correlated with the loose gravels and quicksands found at Sulphur Mine. This tighter formation disallowed the escape of much more water than at Sulphur Mine and Bryan Mound which was plagued with a great amount of cavity and fissure area and cold water. The greater thermal efficiency of Big Hill reduced the amount of hot water required to produce a ton of sulphur (the water ratio) compared to the other two domes. Production was expected to be only 1000 tons a day, but while still using the 1000-ton equipment the Gulf site was able to produce 4000 tons a day. The total production from Big Hill's lifetime was 12,346,000 tons of sulphur.

The war's ending brought a crisis to the industry of overproduction. Union and Freeport stockpiles were in the million range, there was an overabundance of sulphuric acid and sulphur chemicals, and the government had a surplus of 150 million pounds of oleum and sulphur itself. Industrial activity was down, and farmers had planted fewer crops needing less fertilizer.

The markets demanding Frasch sulphur were basically the rubber and paper industries. The other markets were being shared by abundant pyrite supplies, sulphur recovered from metallurgical processes, and from petroleum and gas refining techniques (sludge acid).

The Union Sulphur Company already was established in the market. Frasch was able to sell to large industrial consumers, chemical jobbers, and sulphur refiners who made the "flowers of sulphur" popular with the producers of powdered sulphur produced for the spraying of vineyard crops. He stated one open price F.O.B. (producer pays transport costs) plant in carloads, his minimum sales unit.

Freeport, who had to break-into the market, employed the services of Parsons and Petit of New York. They were experienced chemical merchants who had dealt with Sicilian sulphur in the past, and had a quantity of contracts with various buyers already established.

Texas Gulf's entry saw their president, Walter H. Aldridge, as hoping to displace pyrites from the fertilizer industry. He employed the H. J. Baker and Brothers brokerage firm to build up a client list, and later instituted his own sales force.

Domestic and imported pyrites were able to undercut the price of American sulphur from 1919-1926. However, in 1925 native sulphur accounted for 68% of the market where as pyrites accounted for only 19% of the market.[107] The contact process was important in fixing the price of sulphur, and demanded the pure Frasch sulphur over sulphur refined from pyrites.

The foreign market was again invaded, and this time by all three American companies. The Sicilians were determined to hold on to the European market. They made a firm agreement with the National Sulphuric Acid Association of London, which was Europe's largest consumer of sulphur from 1922-1925, and also reduced prices for all their customers in general.

The American companies sought to establish a workable agreement with the Sicilian industry in order to divide the world market between them in a suitable fashion. These negotiations were hampered at first by the American companies acting as individual interests instead of as a single entity. The companies formed the Sulphur Export Corporation, known as Sulexco, under the Webb-Pomerene Act.[108] This act allowed American companies to unite for bargaining in foreign markets, and solved the problem of dispersed negotiations with the Sicilians.

An agreement was finally reached between the two factions which guaranteed 135,000 tons of trade to the Sicilian industry.[109] The world market was then divided in such a manner as to give Sulexco 75% of the world market and the Consortium 25%. The low American prices in North America stopped Italy from entering North American markets, and no American sulphur entered Italy due to a national law barring any importation of foreign sulphur. Minimum prices were to be agreed upon yearly, and the agreement lasted until 1934.

The domestic market saw healthy growth in the 1920's. The paper, insecticide, and rubber industries grew enormously. Sulphuric acid manufacturers switched to purer Frasch sulphur as the acid consuming petroleum and fertilizer industries expanded and the chemical industry demanded more sulphuric acid as new products were invented (such as rayon, plastics, and refrigeration). The year 1929 saw 70.8% of all sulphuric acid being made from 1,135,000 tons of Frasch sulphur. The sulphite paper pulp industry had also doubled. This greatly increased demand for Frasch sulphur brought about the further exploration of untested domes by the American industry.

The Union Sulphur Company investigated four domes from 1920-1922. One was at Palangana near the Mexican border in Texas, and another which they optioned the sulphur rights to in 1922 was Damon Mound.

Damon Mound proved to be unprofitable for the company after some fifty-two test wells had been drilled. The only good deposit amounted to less than 120 acres. Union decided to abandon the mound.

Big Creek was the next dome investigated. Union set up production here, but was able to produce only 1070 tons of sulphur from six wells. Twelve other domes were explored of which none were steamed.

Union's Sulphur Mine operation was closed down on December 23, 1924. It had produced 9.4 million tons of sulphur during its operational lifetime. The company was able to sell from stockpiles for three years, but they were no longer a producing factor in the industry.

The salt domes of Louisiana and Texas which showed any promise of sulphur were all explored. Unfortunately, of the more than 200 salt domes in the area, only 24 domes ever produced sulphur and by 1958 half of these had been abandoned.[109]

The big find of the 1920's was at Hoskins Mound in Brazoria County, Texas. The Producer's Oil Company, a subsidiary of the Texas Company was drilling for oil under the guidance of chief geologist E. G. Woodruff. His idea was to drill deeply on the flanks of the dome.[110] The third well they drilled on the south flank found a sulphur bearing formation 200 feet thick. The find was ignored, and not until Texas Company No. 10 was drilled did the company take notice.

The Texas Company was inexperienced with sulphur deposits so they called in the expert, Spencer Browne. He in turn called in Lundy from San Francisco. A sulphur survey was taken, and a report turned into the Texas Company. The Texas Company was interested in mining the sulphur themselves, but preferred to sell the property to either Texas Gulf or Freeport.

Freeport purchased the Texas Company lease solely for the production of sulphur. Construction of the plant was begun, and the operation was assigned a deadline for the production of sulphur of one year. The Texas weather and labor problems hindered the mine's construction. However, sulphur flowed on March 31, 1923 a day before the deadline date.

The plant was built 2000 feet off the ground to defeat subsidence which had been a problem at the Sulphur Mine operation. Every mine had improved in technology and working efficiency from the beginning at Sulphur Mine. Hoskins was no exception with an 8400 hp boiler that could develop 50% overload and a gravity canal extending from Bastrop Bayou which provided 280 million gallons of water to reservoirs, a three-month's supply.

The mound at first refused to produce economic sulphur. The salt dome is small, and there are large boulders in the overlying sand and unconsolidated sediments which hamper the successful drilling of the dome. Drilling was further slowed by the 100 foot overlying cap rock which is very hard and dense. Finally, the richest sulphur deposits are found on the south and east flanks (not on top), and are located at a depth of 2000 feet.

The cap rock, once penetrated, was found to be cavernous and allowed the hot water to migrate to the center of the dome. A successful mudding operation was developed to fill the major cavities inside the dome. The thermal efficiency of the dome was brought to a normal level and subsequently production.

Expected subsidence did not appear in the dome. This subsidence is depended on to close the cavities created by sulphur extraction. The closing of these cavities is necessary to make the next well thermally efficient. Nitroglycerine was exploded to induce subsidence, but finally subsidence naturally occurred. The thermal efficiency of the Hoskins location became very good, and the dome became a good sulphur producer.

The next property explored for sulphur was located in Wharton County, Texas. The dome was proven on August 31, 1923 with shows of both sulphur and oil. Exploratory drilling determined the sulphur deposit to cover about 1500 acres on the eastern and southern slopes of the dome. The cap rock contained as high as fifty percent sulphur in places, and the thicknesses sometimes were in excess of 200 feet.

The purchase of leases and this exploratory drilling extended over a period of approximately five years. The construction of the plant did not begin until May 31, 1928. It was an enormous project because of the extensive area of the sulphur deposit, and because of the individual leases which required a separate operation be applied to each lease. Usually a deposit is mined by a tight concentration of wells beginning at the highest point of the sulphur bearing area and travelling down the side of the dome. Subsidence then naturally closes the cavities caused by the sulphur extraction. This method can only be followed if the property is owned in total or if the individual leases are pooled together. This pooling was accomplished for about half the leases, but the other half still required separate operation.[111]

It was determined that eight million gallons of water would be necessary to steam the wells over every 24 hour period. The main water supply was nearby the San Bernard River. Well water high in bicarbonate of soda was added to the surface water providing the "soda" for the process of lime-soda softening which protected the pipes from corrosion and scaling.

The power plant was located away from the dome to be unaffected by subsidence. Superheated water, steam, and compressed air lines totaled 90,000 feet in main feed length and 26,000 feet in secondary pipe. The sulphur production lines including steam lines to prevent freezing reached 80,000 feet in total length.[112]

The Boling Dome was the first operation located inland from the open ocean. This forced the bleed water from the operation to be aereated and settled before it could be returned to the San Bernard River below tidewater where the river was already salty.

The town of Newgulf grew up alongside the sulphur operation. It became a complete and modern community without company ownership of any of the business establishments. It is a thriving community as is the whole of Wharton County thanks to the increased tax revenue produced by the Boling Dome sulphur operation.

The Boling Dome became the largest producer of sulphur found in the industry, and had produced 50 million tons of sulphur by January 1958 which accounted for about 38% of total Frasch sulphur production.[115] Boling was still producing 1.5 million long tons a year in 1978.

The Texas Gulf Company also developed a small deposit at Long Point, approximately twelve miles northeast of Boling. A single well was steamed, and produced 402,000 tons of sulphur from March 19, 1930 to October 19, 1938.[116]

A new company arose from the development of another small deposit located between Corpus Christi and Laredo. The dome, named Palangana, was investigated by J. W. Cain and A. H. Smith who obtained good shows of sulphur.

They decided to develop the south Texas dome on their own after both Union and Texas Gulf rejected the opportunity to develop the dome. Cain and Smith organized the Duval Texas Sulphur Company. The small plant was operated efficiently, and produced 237,689 tons of sulphur from early 1928 until the spring of 1935.[117]

Duval also purchased a block of leases on the Boling Dome through a royalty agreement with Texas Gulf. Duval began steaming the well in 1935 and extracted 571,237 tons of sulphur before closure in 1940.[118]

Duval also explored the Orchard dome for sulphur between 1929 and 1930. Their initial investigations found no commercial deposits on the top of the cap, but Gulf Oil discovered sulphur on the flanks of the dome. Duval was then successful in locating good deposits along these flanks. These deposits were discovered in the hollows of step faults in the overhanging limestone some 1200 to 2500 feet deep, or in narrow structures between faults at depths between 2500 to 4000 feet.[119]. Sulphur was found in the salt, or in one pocket on top of another which required two wells to be operated simultaneously, one directly over the other. Steaming began in 1938.

This structure provided deposits of both large and small quantity, and became a very profitable reserve for the new Duval company, as it had produced 3,735,000 tons of sulphur by 1958.

The Jefferson Lake Oil Company was exploring salt dome property back in Louisiana during this time of development in Texas. Their activity was concentrated on 2500 acres of land surrounding the Jefferson Island salt dome. This land was leased from the Louisiana state government with a one-eighth royalty to be paid the state on any oil, gas, or mineral resource discovered. The company spent about a million dollars exploring for oil and came up dry on every hole. However, in their last try they discovered a good show of sulphur beneath Lake Peigneur.[120]

Jefferson Lake leased the property to the American Cyanamid Company which withdrew after six months of attempted development. Jefferson Lake then went into the sulphur business, and became the Jefferson Lake Sulphur Company. Jefferson Lake successfully developed the Lake Peigneur property, but produced only a marginal 426,235 tons between October 18, 1932 and June 1936.

They next explored the Clemens Dome located in Brazoria County, Texas near the San Bernard River. Jefferson Lake's exploration began on September 21, 1936, and through drilling had outlined the sulphur deposit within two months. The entire Lake Peigneur plant was then dismantled, moved, and reassembled at the Clemens site. Sulphur production began on April 27, 1937 and continued for five years. The operation was now concentrated on the lower end of the dome, and it appeared a good mudding operation was needed for continued production. Duval and Freeport generously allowed Harold Jaquet, Jefferson Lake's field superintendent, to inspect their mudding operations.[121] A suitable mudding operation was then employed at the Clemens site and production rose again to acceptable levels in 1942. The dome had produced a total of 2,626,130 tons by December 1, 1956.

Jefferson Lake also developed an operation at Long Point with half of its production guaranteed to Texas Gulf, the provider of the leases. The plant steamed their wells with a 3,380,000 gallon a day capacity. The operation produced 2,396,000 long tons of sulphur from June 7, 1946 until 1957, and was still producing 400,000 long tons of sulphur a year as of 1978.

The Grand Ecaille dome located thirty-five miles south of New Orleans and ten miles southwest of the Mississippi River became Freeport's next site of sulphur extraction.[122] The cap rock area covers about 1100 acres and averages 250 feet in thickness beginning at 1250 feet below the surface. The overlying formation consists of sand and unconsolidated sediments.

A ten mile long canal was dug from the Mississippi River to the wellsite to provide 2,000,000 gallons of water to steam the wells every 24 hours. A shipping terminal and headquarters for the operation were also established next to the river.

The plant itself was constructed upon 18,000 pilings supported by a concrete mat. The plant floor was raised eleven feet above the water's surface. All permanent buildings were constructed of steel and engineered to survive 125 mile per hour winds.

The power plant consisted of six 860 hp. Sterling boilers which were able to use gas, oil, or pulverized coal. Three 750-kilowatt noncondensing turbine generators provided current for all the necessary operations found on the plant. Three 800-pound high-pressure compressors supplied the air for pumping sulphur. Steam used for auxilliary mechanisms (generators, compressors, pumps) was returned to the hot-water system by low-pressure heaters and water treating plants. This steam provided approximately 30% of all heat being applied to the sulphur deposit. The operation showed considerable improvement over Herman Frasch's original operation of four decades earlier.

The Grand Ecaille dome was plagued by a cavernous cap rock structure similar to Hoskins Mound. Dredged material was used as the raw material in the mudding operation to cure the thermal deficiency.

The Grand Ecaille dome presented the Freeport people with a new problem; first appearance of "off-color sulphur" due to traces of crude oil in the mineral. The problem was solved by Freeport's development of a distillation process which removes the unwanted oil from the sulphur, and turns the sulphur into "bright sulphur". This problem has arisen in salt domes in Louisiana and Mexico, and is handled by different refinery techniques of the individual producer or sold as off-color sulphur and refined by the buyer.

Freeport was hesitant in opening its operation at the Grand Ecaille location due to Governor Huey Long's administration and its tax policy. The tax policy began with an ad valorem tax on the estimated size of any mineral deposit. The estimation of a sulphur deposit in a Frasch operation cannot be done visually as no man can descend to the sulphur deposit for its visual inspection. It is also evident that a sulphur deposit can be quite irregular within a cap rock structure. The sulphur once melted hopefully flows to the pool area. It may also migrate to any part of the dome where gravity might take it, and be frozen in an unminable fissure forever. Bryanmound is a good example of a poor estimation of a sulphur deposit. The estimate was seventeen million tons, but in reality only five million tons were produced.[123] Therefore, the estimation of a sulphur deposit is a very crude and "blind" figure.

Taxes levied against Frasch sulphur also are unfair due to the unequal representation it receives in the state legislature. Only six counties in Texas produce sulphur out of a total of 254 counties. State severance taxes reflected this prejudice as they have always been considerably higher than those levied against other minerals (for example in 1936 the sulphur tax was 8% of value as compared to the oil tax which was $2\frac{3}{4}\%$ of value). An ad valorem tax, which remains on the sulphur year after year as long as the sulphur remains unsold, and federal and local taxes increase the final tax bill to over six dollars a ton.[124]

Union Sulphur Company ended its operations due to the ad valorem tax either because it was paying on 1,000,000 tons of sulphur which did not exist or, if it actually existed, because production was out-balanced by the tax.

Louisiana groups interested in the industrialized growth of the states, such as the New Orleans Association of Commerce, did not want a situation of this sort to arise again. A ceiling was put on the ad valorem tax limiting it to twice the property value of the plant's location. They also pushed for legislation that would bring the stature of sulphur in line with that of oil and gas. Oil and gas taxes could not be raised or newly imposed on rights, leases or on property which contained oil and gas. The legislature agreed to this proposition and Freeport began construction of its Grand Ecaille plant.

The legislature then proceeded to raise the severance tax to $2.00 a ton, 77 cents above the Texas severance tax. Texas production correspondingly increased while Louisiana production correspondingly decreased. Fortunately, the severance tax was brought to parity with the Texas tax due to the work of the Louisiana State Board of Commerce and Industry during the Governor Leche administration.

The final tax battle was begun by Earl Long when he took office eighteen years after his brother's departure. Earl proposed a $3.00 a ton severance tax which would have cost Freeport four million dollars a year in taxes. A large publicity campaign was put forth by Freeport to defeat the proposed law labeled House Bill 671. The campaign drew support from the people and press of Louisiana, and from the sulphur dependent industrial interests outside of the state. House Bill 671 and all its amended versions which reduced the tax down to $2.00 a ton were defeated. The $1.03 a ton severance tax remained intact as well as Freeport's competitive standing in the industry. These events came near the beginning of World War II.

World War II brought an increased demand for sulphur similar to that of World War I, as well as the end of agreements between Sulexco and the Italian sulphur industry. The Gulf Coast companies responded by producing a million more tons a year. Their stockpiles were also reduced by a half a million tons a year.

The postwar era saw a boom in chemical activity as industry and technology expanded. The Korean War brought an even greater demand for sulphur than World War II, resulting in an increase of production of a million tons a year. The demand outstripped production, and reduced stockpiles from 3.5 million tons in 1945 to 2.7 million tons in 1950, a quantity of only six months supply. This demand caused a shortage of sulphur in 1950 which was not long lived, but resulted in a more intensive search for sulphur across the world. The advent of synthetic materials such as fibers, rubbers, plastics and resins, gum and waxes, dyes and scents, detergents and lubricants, and others have greatly increased the demand for sulphur, and the subsequent search for new sulphur deposits.

Sulphuric acid consumption rose from 4.8 million tons in 1939 to 8.17 million tons in 1945. The demand for sulphur jumped from 2.5 to 3.8 million tons during 1940-1945 with 712,000 tons a year going to our allies which equalled about one-third more than our pre-war exports.

The fertilizer industry expanded from 8.2 million tons in 1940 to 18.0 million tons in 1950. The demand on H_2SO_4 was increased by 3.33 million tons in the production of super-phosphate and ammonium sulphate for these fertilizers. The fertilizer industry not only received increased demand at home, but also from the new consumption of the underdeveloped countries.

The American chemical industry increased its consumption of sulphuric acid from 0.6 million tons to 3.8 million tons between 1939 to 1951. The growth of the synthetic fiber industry brought a great new demand for sulphuric acid with the rayon industry bringing about an increase in demand of 4,350,000 tons sulphuric acid by itself. The products such as pigments, synthetic rubber, and petrochemicals (plastics) also increased the demand for sulphuric acid. The demand equalled 4,350,000 tons of sulphuric acid by 1956 in the chemical industry opposed to 682,000 tons in 1925.

Direct use of sulphur was increased in the paper pulp process where demand increased half over its pre-1940 demand. There was an increase in demand for carbonibisulphide in aluminum manufacture, and for the vulcanization of natural and synthetic rubber.

Sulphur stockpiles decreased after the war with continued demand from Europe. Sulphur was used by the western European countries to build-up munition supplies in order to strengthen their military posture opposing the communist bloc. The greatest reason for the shortage of sulphur which developed was the Korean War.

Texas Gulf and Freeport remedied the shortage by reducing supplies to domestic consumers by 80-85% in 1951. Exports were put on allotments causing protests by the importing countries throughout the world. These actions were initiated by the National Production Authority.[125] Other actions of the NPA were limits on consumption by small users in the U.S., and on the inventories they could hold.

The exploration for increased sulphur production by various means was undertaken to a greater extent. Surface deposits were mined in the United States and overseas. Overseas pyrite production was also increased. The United States and Canada recovered more sulphur from sour natural gas, refinery gases, and from smelter gases.[126] A sulphuric acid production process using gypsum as raw material was devised in Germany. The search for new Frasch domes in Texas, Louisiana, and Mexico successfully provided the most substantial supply of sulphur.

The Jefferson Lake operation at Starks in Calcasieu Parish, Louisiana began processing on June 25, 1951. This was the first operation to begin after the Korean War. The property had been released to the Jefferson Lake Company by Texas Gulf who was busy developing the Moss Bluff, Spindletop, and Worland domes. The negotiation was as usual a royalty agreement.

The sulphur was extracted from the lower edges of the dome. The plant handled 1.5 million gallons of water a day, and produced 39,488 tons of sulphur (in six months of 1951). The output was increased to 110,528 tons in 1955.

Texas Gulf's development was planned to begin in 1939. A series of economic circumstances (i.e. the Great Depression), and then the military closing of the plant assembly during World War II to divert its machinery and manpower to other needy sectors delayed further development. The construction of their Moss Bluff operation began in 1947, and the plant was producing by June 24, 1948. The dome produced 2,613,747 long tons of sulphur up through the end of 1957.

Spindletop was brought into production on May 12, 1952 after forty-two exploratory wells had outlined the sulphur deposit in 1950. The plant was also designed to accommodate the previously existing city of Beaumont, Texas. The total output was 2,110,000 long tons of sulphur through 1957, produced by the 4,000,000 gallon per day plant.

The Hoskins Mound Freeport facilities were closed after thirty-two years of operation in May 1955. The plant had produced 11,000,000 tons of sulphur over its lifetime. Freeport now investigated Garden Island Bay at the mouth of the Mississippi River in extreme southeast Plaquemines Parish, Bay St. Elaine on the Gulf 100 miles westward, Lake Pelto in central Plaquemines Parish, and an unprosperous venture at Dog Lake in Central Terrebonne Parish.

Garden Island Bay had formerly been explored for oil by the Texas Company from whom Freeport attained the rights to the four domes. The sulphur company then located brimstone in 1200 acres of cap rock at a depth of 1600 to 1700 feet.

This plant was also built on a concrete mat on which were positioned 2260 pilings. The plant was raised sixteen feet above the marshy surface to avoid the spring floods. The plant had a 3.5 million gallon a day water capacity, but usually steamed ten to twelve wells at three million gallons a day. A billion and a half gallon reservoir was constructed on 600 acres of marshland. There were no vats at Garden Island Bay as the molton sulphur was transferred directly to "hot barges", and then shipped to Port Sulphur for distribution. The plant began production on November 19, 1953, and had produced 2,318,000 tons through 1957.

Bay St. Elaine, another near shore dome was brought into production on November 19, 1952. This plant was not built on a concrete mat and pilings, but was a floating structure which was anchored at the site. The plant was equipped with five gas-fired boilers, and produced 2,000,000 gallons of super-heated water daily. This was also the first plant to use seawater in the mining process, and utilized a softening process which successfully eliminated magnesium hydroxide, calcium carbonate, and gypsum alkalines.

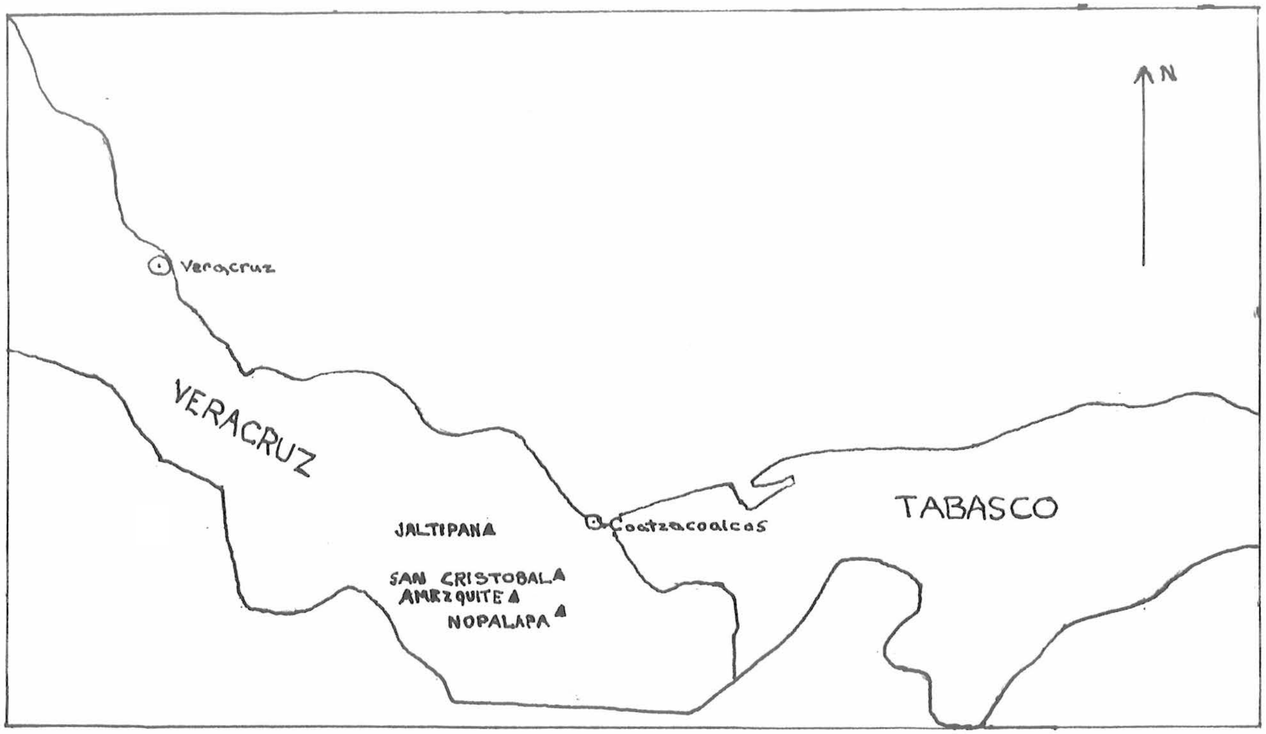
Upon the depletion of the reserves at Bay St. Elaine in 1959, the plant facilities were disassembled and moved to the adjacent Lake Pelto property which lay under eight feet of highly saline water. The Lake Pelto operation was a good producer of sulphur until 1974.

Freeport also developed the Chacahoula dome in extreme west Lafourche Parish. A thin sulphur deposit appears on this dome's southern extent. This location was used as an experimental station for Freeport's new vatting process. The molten sulphur was run over steel belts and flaked to lower dust loss encountered in loading and unloading. The dome had produced 291,000 tons from February 1955 to December 1957.

There were seven new domes exploited in the 1950's. The small producer of the Jefferson Lake Sulphur Company at Starks; the small producers of Nash, Bay St. Elaine, Chacahoula, and a large producer at Garden Island Bay all owned by Freeport, and the large deposits at Moss Bluff and Spindletop owned by Texas Gulf. These domes significantly strengthened the reserves of the American Frasch sulphur industry.

The Mexican sulphur industry was also growing during the 1950's. Mexican sulphur shows had been found by oil drillers as far back as the early 1900's mostly in the Isthmus of Tehuantepec. Seventy domes had been discovered by 1917, and about forty of these showed sulphur. However, the sulphur deposits were ignored by the oilmen.

Frederico Dechamps did the first constructive work involving Mexican sulphur by cataloging the location of known sulphur domes in 1936. He described the Petrerillos, Jaltipan, Teterete, and San Cristobal domes as having accessible routes of transportation to the Port of Coatzacoalcos, and prime targets for development.



SULPHUR BEARING SALT DOMES OF THE ISTHMUS OF TEHUANTEPEC, MEXICO

Map 3.
Illustration 4.

The next sulphur pioneer was Alfredo Breceda, who with the aid of engineer Manuel Urquidi investigated the wellsites where sulphur had been located. Together they completed a thorough surface survey of the area.

Breceda obtained the first sulphur rights in the Isthmus of Tehuantepec on June 15, 1942 which were granted by the Secretary of the Economy and the Fomento de Minero (Commission to Promote Minerals).[127] A four million acre area of land was delineated by the Mexican government to be the area of sulphur production, and was named the Sulphur Reserve.

The concession granted to Breceda by the Fomento allowed him to search for sulphur in an outlined area, and to work any discovered deposit in this area. These concessions were only granted to Mexican citizens or Mexican companies. A large area was allowed to be explored under the concession, but only a much smaller and more specific area was allowed to be mined. This was established through a contract entered into by the operator and the Mexican government. The contract specified when the plant must be completed, and the amount of royalties to be paid to the government.

Breceda began his official minimal exploration in June 1952, while he simultaneously searched for financial backing. He was turned down by the Mexican president and government, the major banks, and the rich personage of Mexico because of the intangibility of the sulphur. Breceda was then introduced to the Brady brothers, drillers originally from Louisiana who had grown wealthy from wildcatting for oil in Texas and Venezuela. Breceda-Urquidi, and the Brady's formed the Azufre S.A.[128]

The San Cristobal dome was the first dome to be explored. The property was surveyed, and then for a year and a half the Brady's collected financing and equipment under the name of the Cia. Mexicana Minerales.[129]

The first hole was drilled on April 1, 1944, and the equipment failed in the process. The third hole showed sulphur, and at this time the San Cristobal dome concession was turned over to the Mexican Gulf Sulphur Company.

The Brady's now moved to the Breceda-Urquidi concession near Jaltipan. The old oil field was located by seepage, and the remnants of old equipment. Sulphur was found in the first drilling. The brothers now moved across the Chachalapta River to Potrerillos. Sulphur was quickly found, and the option on the concession as purchased by the Pan American Sulphur Company. The Brady's moved back to San Cristobal, but soon were exploring the Mezquital and Vista Hermosa domes that lay on the other side of the Coachapan River. Brady drilled off-set to the old Amezquite No. 2 which had found sulphur at 1042 feet, and again found sulphur in the first hole.

The Vista Hermosa dome was discovered by the Brady Brothers, and consulting geologist Walter H. Maddox. He discovered the dome by scrutinizing five conspicuous surface points. Drilling at these points, and assistance from aerial photography proved the existence of the dome. It was the first dome in this region to be discovered by surface geology. His geological reports were the basis of the creation of the Gulf Sulphur Corporation. This brought the total to three Mexican sulphur companies sponsored by the Brady brothers drilling.

The American sulphur corporations had declined all offers of exploration in Mexico during the 1940's. The concepts of unknown taxation by the Mexican government, ability to drill in the jungle, ease of mining, production and transportation in the U.S. versus Mexico during World War II, and a healthy abundance of sulphur in the 1940's kept the American companies exploring Louisiana and Mississippi at that time. It was not until 1949 that the Texas Gulf corporation began exploring the Nopalapa concession near San Cristobal.

San Cristobal had produced its first sulphur on March 15, 1954 for the Mexican Gulf Sulphur Company. Impatience and inexperience caused this operation to become unsuccessful. Financial pressures caused much of the problem and low production was its final end.

The Mexican Gulf Sulphur Company was the first company setup by the Bradys. Mexican Gulf had purchased two concessions from Bradys' American Sulphur Company. The Bradys had drilled ten wells with sulphur shows, and with the help of consultant geologist Walter Maddox, ten more wells were drilled on 125 acres.

The tight structure at San Cristobal required the drilling of bleedwells to allow the drainage of excess cold water. The dome then came on stream on March 15, 1954. Production averaged 7454 tons per month for September and October. This was half the expected production. An increase in water capacity from one million to two million gallons a day was planned to increase production. The financial backing for this expansion came from Houston which became the monetary headquarters of the Mexican industry.

The production still did not rise to profitable levels, and it was determined that the deposit was far more inconsistent than the original rich cores had shown. A greater amount of exploration should have been undertaken to define the true potentials of the dome. Another realization was that the anticlinal structures relating to the salt domes in the Isthmus may or may not be suitable for the Frasch process.

The Pan American Sulphur Company was incorporated April 17, 1944 with Texas backing.[130] Their propsect was the Jaltipan-Potrerillos dome area.

Sixty-nine cores had been obtained by April 1952, and had relinquished evidence of a rich sulphur deposit. Reserves were estimated at 7,257,401 tons in a twentieth of the company controlled area.

The plant was begun in September 1953 and was finished within the year. September 24, 1954 was the first day of production with two million tons of sulphur produced by April 10, 1957.

The Mezquital dome was located on the Coachapan River abbve San Cristobal. Sulphur was first produced here on May 3, 1956 by Cia. de Azufre Veracruz S.A., a subsidiary of Gulf-Sulphur Corporation. The Mezquital potential was estimated to be about eleven million tons proved and an additional 3.2 million probable tons.

The Soledad dome, two miles northeast of the Mezquital dome, was drilled by Gulf Sulphur who found a cap rock which contained 14% sulphur. The company set up one of the most sophisticated and automated plants of the time to work the deposit. The total design was very compact in nature, and a precise record of temperatures and pressures was kept for each well by instrumentation. A great reservoir of hot water was maintained to rescue any well which came under undue stress. A zeolite water system disposed of hot lime-soda tanks and insulation on the pipes.

Mezquital production was greatly improved by a large ratio of bleed-wells to production wells. Hot water input was concentrated by very closely spaced producing wells. Hot-water and air capacities were also raised, increasing production to a thousand tons a day, while continued exploratory drilling proved a great amount of additional reserves in the surrounding cap rock.

Texas Gulf Sulphur Company began operating through its subsidiary Cia. Exploradora del Istmo, S.A. in August 1949. Unlike the other operations set up in Mexico, Texas Gulf already had money, experienced personnel, and equipment with which to begin its project. Their best property was established to be the Nopalaca dome after aerial surveying, geophysical testing, geological investigation and core drilling of over 450 holes in 28 structures.

The plant for Nopalaca was built on the Houston Ship Canal and shipped on barges to the Moss Bluff dome where it was tested for proficiency. It was then barged across the Gulf of Mexico in June 1956, and finally up river to the plant site. This system solved the problems of building a whole new plant in the jungle. The transportability of the plant allowed it to be moved to a new location, and to begin processing in a short time.

The Mexican sulphur industry had advantages and disadvantages compared to the American industry. One disadvantage was the anticlinal structure of the domes which creates irregularities not seen in the regular mounds above the American domes. The two most serious problems caused by these irregularities were tight cap rocks and fissurous cap rocks. The former was solved by sophisticated drilling techniques and bleed wells while the latter was solved by an adequate mudding operations.

Uniformity in depth of sulphur placement was another problem. The deposits varied in depth according to a north-south trend which extended across the dome. The Mezquital dome produced sulphur in the southern zone at a depth of 180 feet. Here the mineralized zone was less than 100 feet thick. The northern end contained sulphur in very small quantities and at a depth of 1110 feet. Between these extremes the depth of placement increased with a constant slope, and thickness increased to as much as 900 feet at approximately the center of the traverse. Three-quarters of the distance across the traverse thicknesses had been reduced to approximately

250 feet until the northern extent was reached where only a few tens of feet of sulphur were seen, and eventually the end of deposits appeared.[131]

The main advantage of the Mexican sulphur domes were their great supplies of silt free freshwater which needed no settling. This supply was drawn from abundant rivers and lakes. The Mexican sulphur industry was bolstered by the great oil and gas fields contained in Mexico. These fields supplied the sulphur plants with plentiful and cheap fuel to drive their facilities.

A turbulent Mexican political scene has sometimes hampered the industry. Accusations of unfair labor practices, and wage scales were often targeted against the operations run by United States backing, and against politicians who were friendly to these interests. The result was bad for Mexico's image of stability above the border, and for its public and labor relations at home.

Despite any and all obstacles the Mexican sulphur industry was established very quickly, and significantly. This was done by undercutting American sulphur prices to obtain a substantial portion of the market. In 1955, Mexican sulphur was offered at three dollars a ton less than American exports, and two dollars a ton less than American sulphur in the United States. This action disrupted the stable and narrow profit margin of the sulphur industry.

The Americans reduced prices to remain competitive, and from 1955 when the price of sulphur was $31.00 a ton for bright, and $30.00 a ton for dark, the price fell to $25.00 a ton for bright and $24.00 a ton for dark sulphur in 1957. Mexican sulphur remained cheaper than American.

The effect of the lowered sulphur prices on the consumption industries was minimal. The sulphuric acid trade, which was accused of high prices by its consumers, actually wanted to raise their prices. However, this was made impossible by the lowered sulphur price.

There was no sudden increase in the buying of sulphur due to the lowered Mexican prices, and never is in the sulphur market as a rule. Consumers of sulphur are in industries where their demand stays constant with their level of production. However, the increase in sulphur prices will send the consumers searching for alternative suppliers such as pyrites or H_2S recovered sulphur.

The effects of these alternative sulphur producers sets the ceiling for the Frasch sulphur, while the highest-cost high water to sulphur dome sets the basement. Competition intercedes between these two extremes. All consumers of sulphur demand an equal, and stable price be set because none wish to have their opposition obtain sulphur at a cheaper price.

The American industry saw the entry of a short-lived competitor, Standard Sulphur, in November of 1953. Their operation at the Damon salt dome produced 139,618 tons of sulphur before exhaustion in April of 1957.

Texas Gulf also began exploitation of the Fannett salt dome in 1958. The dome produced 195,390 long tons that year. Texas Gulf was also preparing to mine the Bully Camp dome in Louisiana at that time.

The American companies were also diversifying in the 1950's. The Duval Sulphur Company became the Duval Sulphur and Potash Company. Seventy percent of their sales in 1957 were made in the potash market. They also expanded into copper and molybdenum.

Jefferson Lake Sulphur Company began processing sour gas in British Columbia to recover elemental sulphur, as well as the Manderson sour gas field in Wyoming. The Wyoming processing operation contributed about fifty-five tons a day between 1955-1958. They also became active in the oil and gas industry in Louisiana, Texas, and Oklahoma including a natural gas processing plant which recovers gasoline, and liquified petroleum gases from the natural gas.

Jefferson Lake also entered the petrochemical business. Their original products were cresylic acid and sodium sulphide.

Freeport expanded into the manganese industry by processing low grade ore in Cuba. They became the largest manufacturer of manganese in the western hemisphere through this processing plant during World War II. They also helped the war effort by developing a nickel oxide plant at Nicaro, Cuba in 1957. The ores were concentrated at Moa Bay in Cuba and then were separated at the refinery at Port Nickel below New Orleans.

Freeport also began exploration and production in the oil and gas industry producing 2,245,000 barrels of oil in 1957. They also became involved in the potash industry through the National Potash Company which was jointly founded by Freeport and the Consolidation Coal Company. They also were active in pyrites and operated a sulphur recovery plant in New Jersey.

Texas Gulf's only expansions were in oil production at Boling, Spindletop, and Moss Bluff, and further exploration for oil in Texas and in Canada. Texas Gulf entered the recovered sulphur market by refining hydrogen sulphide and sulphur dioxide gases, and also began exploring for minerals, mainly copper-zinc sulphide and zinc-lead-pyrite ores.

Offshore sulphur prospects were viewed as potentially very productive at the end of the 1950's. Statistics suggested that out of 125 underwater domes fifteen should be sulphur producing. Humble Oil and Refining Company located a dome about seven miles offshore. Fourteen test wells proved the sulphur bearing cap rock to be between the depths of 300 to 600 feet. Reserves were estimated to be between thirty to forty million tons.

Freeport was chosen by Humble to work the dome because they were the first company to use seawater in the Frasch mining process, and because they had the greatest experience in underwater operations. The Grand Isle plant posed challenges to construction because of its vulnerability to 100 mile per hour winds, waves reaching over forty feet high, and extreme problems of corrosion in the open Gulf. Subsidence could draw the plant under the ocean's surface.

Freeport constructed a huge Y-shaped structure at a cost of $30 million, with offshore technology accounting for $8 million of the total expense. The complex dwarfed any offshore oil platform as it was a mile long, stood seventy-five feet above sea level, and was built to support drilling rigs and the rest of the mining facilities. The complex, which was begun in June 1959 and completed in 1962, became one of the world's largest and most efficient Frasch operations.

The sour gas industry was intensely being developed in the 1950's. The greatest production was located in Canada with plants also operating in the United States, Mexico, and France. The influx of sulphur into the market from these operations began to effect the sulphur market.

The removal of H_2S from sour gas began in the 1940's. Two programs started simultaneously in Arkansas, one by Texas Gulf Sulphur in a plant near McKamie, Arkansas and the other by Southern Acid and Sulphur Company in cooperation with the Ohio State University Research Foundation at Magnolia, Arkansas.[133]

The process first concentrates, and cleans the gas in monoethanolamine. It is then dehydrated in a solution of amines and glycols to an average of 58% hydrogen sulphide, 41% carbon dioxide, and 19% mixed hydrocarbons.[134]

The Claus method which originated in the 1880's transformed hydrogen sulphide to elemental sulphur and water by introduction of a ferric oxide catalyst. The results were a 120 ton a day plant at McKamie in 1944, and an equally producing plant at Magnolia in 1946. Texas Gulf meanwhile built the Worland, Wyoming plant which produced 400 tons a day since 1949, and was for many years the largest plant in North America. Hydrogen sulphide recovery at the time, produced less sulphur by at least half than that of a good producing salt dome. Operation costs were less, and the H_2S gas was easily obtained which made H_2S recovered sulphur a competitive factor in the sulphur market.

The number of H_2S plants totaled 45 by 1957 and production was up to 484,000 tons. This was only the beginning for large sour gas fields existed along the Rockies from Canada to Mexico. West Texas and Wyoming were predicted to produce 400-500 tons a day for 25 years.

The overriding control on H_2S recovered sulphur was the demand for sweetened natural gas. The facilities to deliver sour gas are costly (the pipeline system). An abundance of sweet natural gas kills off the demand for treated sour gas, and resultingly kills off its sulphur production. The sulphur recovery system must run 24 hours a day with a large supply of gas to be profitable.

The Mexican sour gas industry in 1957 was affecting only the domestic acid producers. Mexico had only one sour gas field at Poza Rica, and in Tabasco. Exploration was being done in the eastern foothills of the Rockies in northern Mexico for additional sour gas.

France in 1957 began processing H_2S in the foothills of the Pyrenees near St. Marcet. The initial production of the plant was the refinement of thrity-seven million cubic feet of gas a day, which produced a subsequent 200 tons of sulphur. In 1959, 185 million cubic feet of gas was refined with the production of sulphur increased to 1000 tons a day.

The result of this field, and the processing was France's sulphur independence. They instead became an exporter of sulphur. This has adversely affected the Texas-Louisiana sulphur exporters as well as the Spain, Portugal, and Cuba pyrite exporters of whom France was a good customer.

It was determined that Canada held tremendous supplies of sour gas. A 1958 find at Beland River contained reserves which approached 10 trillion cubic feet. A flow of 1.5 billion cubic feet a day with 16% H_2S was proven. The total gas reserves of Canada were estimated to be between 200 to 300 trillion cubic feet. The gas in the east plains were sweet and dry while those in the foothills were sour and wet. This sour gas was estimated as being as high as 30% H_2S with the average at about 15%.

Canada's production in 1958 came from six recovery plants each producing 290,000 tons of sulphur a year. The sulphur from these plants was restricted to nearby local markets. The demand here was small. The reason for the restriction was that the sour gas plants were landlocked. It was 600 miles to the Pacific Ocean and 1200 miles to the Great Lakes. The Vancouver Pacific Outlet was reached by inland rail. The price here was \$9.85 a long ton which undercut the Worland, Wyoming prices of \$14.78 a long ton posted to the pulp and paper manufactureres in the northwest. However, the Far East trade, which would have been a favorable target for the Canadian sulphur, was still controlled by the United States and Coatzacoalcos ports.

A possible solution to deliver the sulphur to external markets was to liquefy the H_2S, and then extract the sulphur by the Claus process at these market centers. The piping would easily defeat rail costs. The major problems foreseen were corrosion to the pipe, and the deadly toxicity of the gas if it were to leak out.

Frasch sulphur operations and H_2S recovery plants were judged to be comparable in cost in the late fifty's. Frasch operations held the advantages of lower actual operation costs, and longer operating life. The drilling costs pertaining to development and production were lower within H_2S operations. These variables then tended to cancel each other out.

Both Texas Gulf and Jefferson Lake were in Canada by 1959, with Freeport and Pan America also examining Canada's sulphur potentials. At this time the question of who would actually sweeten the gas, the oil company or the sulphur company, was undecided. Texas Gulf was not concerned about this detail as much as they were of holding on to their share of the H_2S market, in order to protect their interests in the overall sulphur market. They were active in investigating the French water-pressure scrubbing method to advance their operations as far as possible. Jefferson Lake held a 69% interest in their Jefferson Lake Petrochemicals of Canada Ltd. subsidiary which built a British Columbia plant in 1957 with its first shipment going to the northwest territorial paper mills. This plant received the earliest H_2S gas extracted by the Westcoast Transmission Company. Their supply came from 70% of the reserves in the Peace River Area. Jefferson Lake was projected to process all of the Peace River Area, and 80,000 acres in the Calgary Area. They also planned to process the Westcoast Transmission Savanna Creak Area targeted for piping to Idaho. The plants were to be built in East Calgary, Savanna Creek, and Coleman.

Additional factors seen to be coming into play at the end of the 1950's began with the potential reserves of formerly nonconsequential producing nations. The Middle East held great potential for recovered sulphur from their many sour gas fields, and from sulphur contaminated oil. Russia had the potential to produce 175,200,000 tons of elemental sulphur, native sulphur recovered from the Orkla Pyrite Process, and sulphur recovered from Banku oil. Japan and China were seen as potential volcanic sulphur exporters also.

Hundreds of by-product recovery operations were predicted to arise in North America and Europe, and were predicted to capture parts of the sulphuric acid industry's sulphur demand. The recoverers held 19% of the sulphuric acid industry's sulphur demand at the end of the 1950's while elemental sulphur held 70% and pyrites held 11%.

The Mexican industry saw the entrance of a new competitor in 1959 as Texas International Sulphur Company began operating a Frasch plant on its Texistepec Concession. It was a short lived venture, and closed in 1962 after production of only 50,000 tons of sulphur.

American interests in Mexico became stressed in 1961 due to national law which required all mining operations in the country to be owned by a two thirds majority of Mexican nationals. Further pressure was brought to bear on the American companies to Mexicanize in 1965 when the Mexican government instituted export controls on the Frasch industry.[135] This action was taken in order to equalize the size of exports with the expansion of reserves. It also served to motivate the development of a domestic chemical fertilizer industry.

The results of the instituted controls were beneficial as exports increased in 1967 due to the sizable expansion of reserves. A strong fertilizer industry did develop in Mexico, and by late 1966 the largest sulphur producer, Pan American Sulphur Company, was controlled by a two thirds Mexican interest.

The Mexican government gained their wanted control over the industry while the American sulphur companies gained a steady buyer in the developing Mexican fertilizer industry, and also made a good profit on the export of sulphur based on the sizable increases of their reserves. The Americans also enjoyed the benefit of lower taxes while the Mexicans were able to invest in a profitable domestic industry.

In America, the development of the liquid transport of sulphur greatly modified the competitive stance of the American producers in the 1960's. Texas Gulf completed its first liquid sulphur terminal at Cincinnati in 1959 which served the Ohio Valley.[136] A huge facility was completed in Beaumont, Texas on the Neches River in 1960. This terminal handled both liquid and solid sulphur from its four Texas Frasch mines. The terminal serviced rail, truck, barge, and ocean going vessels, and effectively reduced Texas Gulf's handling costs by 30-40 percent. Texas Gulf continued its lqiuid terminal expansion, and by 1963 had ten more terminals completed. A converted 15,000 ton tanker, the S.S. Marine Sulphur Queen, was chartered to ship liquid sulphur to Tampa and the Atlantic Seaboard. It began operation in 1961.

Freeport began in mid-1959 to construct a liquid sulphur transport system. Contracts were made with independent marine transportation companies to build and operate new terminals, and marine equipment costing $20 million. Freeport provided additional facilities at a cost of between $3 to 4 million. They also leased the S.S. Louisiana Sulphur and S.S. Louisiana Brimstone to service its domestic seaboard markets.

The Pan American Sulphur Company constructed its Tampa terminal in 1961 to partially handle its United States imports. This facility was later expanded, and a second terminal was built at Newark, New Jersey. Gulf Sulphur Corporation began operation of liquid sulphur terminals in 1962 at Tampa and Baltimore.

The total number of storage and transshipment terminals in 1963 amounted to twenty-seven for the combined U.S. and Mexican Frasch producers.[137] The two smaller American companies, Jefferson Lake and Duval shipped liquid sulphur by tank truck or railroad car, and did not build any liquid sulphur terminals in the 1960's. Their shipping was still primarily in solid form.

In 1964, Sulexco chartered two 25,000-ton converted tankers, the Naess Texas and the Naess Louisiana, and began transporting liquid sulphur overseas. An $18 million liquid terminal was built at Rotterdam, Netherlands with a 500,000 ton a year handling capacity. This terminal was expanded in 1965, and a second terminal was built at Dublin, Ireland.

The Pan American Sulphur Company began liquid shipments to their Immingham, England facility in 1965. The 60,000-ton liquid terminal was expected to handle 225,000 tons of sulphur a year, and was serviced by three chartered tankers.

Liquid sulphur shiments quickly became the mode of domestic transport increasing from 15 percent in 1959 to an estimated 90 percent in 1963. Liquid sulphur shipping brought advantages to the sulphur producer. They forced the formulation of long-term contracts with the buyer guaranteeing a steady flow of sales for the producer. The additional expense of heated storage forced lower inventories to be maintained by both producer and consumer which also spurred the writing of longer-term contracts. Sulphur producers happily financed consumer conversions to liquid facilities to secure these longer term contracts. The Americans also pushed for the rapid conversion to liquid facilities in order to defeat a Mexican shipping advantage. The Mexicans were able to ship their solid sulphur to the United States on any foreign freighter they were able to secure. The American producers were only allowed to ship their solid sulphur aboard American freighters to domestic ports. The requirement of special vessels to carry liquid sulphur reduced the Mexican advantage.

The change to liquid sulphur delivery was advantageous to the consumers who rapidly complied to the building of liquid handling facilities. Most sulphur consuming processes use sulphur in liquid form including the manufacture of sulphuric acid. The delivery of liquid sulphur eliminated the consumer's energy costs in melting the sulphur down into usable form. The shipment of liquid sulphur defeated the handling losses encountered in shipping dry sulphur which usually averaged about 0.5 percent.[138] Liquid sulphur also could not be contaminated by moisture, scale or other foreign matter, and no dust was produced to corrode adjacent equipment or create an explosion hazard. After the initial cost of conversion was overcome, a plant operated at costs of $2.00 less a ton. Less machinery and labor is needed for the handling of liquid sulphur.

The establishment of the liquid handling of sulphur came at a time of surplus in the sulphur market. The beginning of this surplus period was in 1958. A major price reduction in 1957 by American producers had been aimed at regaining their share of the market which the Mexican producers had taken over. The Mexican producers retained their portion of the market by reducing prices or lowering freight costs. However, the amount of Mexican sulphur imported into the U.S. did level off. The effect on the American producers was their loss of $35 million in revenue from 1957 to 1959.

The Frasch producers began quoting prices on delivery in 1958 which broke with the pattern of f.o.b. quoting which had been in practice since Herman Frasch began selling Frasch sulphur in 1897. Freight allowances and discounts became the competitive variable in securing contracts in the harder fought for markets. The result was the reduction in the importance of the posted price of Frasch sulphur.

The Canadian and French recovered sulphur continued to take more of the market away from the Frasch producers. These increased supplies and the delivery pricing of sulphur caused sulphur to become a regionally priced commodity where transportation costs controlled the success of the producer in a certain regional market.

The Canadians began enjoying a reduced freight rate in rail shipment in 1961 from Alberta to Chicago from $19.94 per ton to $12.88 per ton.[139] This allowed Canadian recovered sulphur to be sold for $26.00 a ton in the Midwest which forced the Frasch producers to lower their Midwest prices to remain competitive. Texas Gulf and Freeport took the Canadian rail rates in front of the Interstate Commerce Commission arguing that the Alberta-Chicago rate equalled the shorter distance rate from the Gulf of Mexico to Chicago. Unfortunately American interests were defeated on appeal in January of 1966.

The American producers, in an attempt to combat the further domestic invasion by foreign sulphur supplies, took a stance of non-competition in the pricing of their sulphur. Through their installation of liquid handling facilities they put an emphasis on customer service and a subsequent closer relationship between consumer and producer.

The four major American sulphur companies reinstituted the Sulphur Export Corporation in 1958 to answer the continuing advances of the Mexican, Canadian, and French sulphur producers. Sulexco once again provided an united front to negotiate with the foreign producers. It also provided technical aid and ocean freight assistance to the American producers as these services became increasingly important with the growth of liquid sulphur transport.

Sulexco had its disadvantages. Not all foreign consumers wished to buy from a marketing cartel. The two larger companies, Texas Gulf and Freeport held the controlling interests in the cartel. They were willing to reduce prices in order to keep sales tonnage up. The smaller companies, Jefferson Lake and Duval, were operating at higher costs with marginal deposits, and could not readily afford these price reductions. Unfortunately, with only a minor say in Sulexco's policy they were forced to have this portion of their output (60%) manipulated by the larger companies.

Sulexco proved to be less than effective in combatting the foreign interests as the American's share of the world market declined by 35% between 1960 and 1963. The major foreign inroad was made by the Lacq, France state controlled producer SNPA which was able to increase its portion of the Western European Market from 25 to 36 percent. This helped the U.S. producers hit a twenty-year low in both domestic and foreign shipments.

In mid-1963, the world sulphur market changed drastically.[140] Demand quickly increased on a large scale, while the small expansion of reserves during the depressed years from 1958 to mid-1963 left the Frasch producers short of supply. This shortage lasted from 1964-1967. During those years, the total increase in consumption in the United States was 32 percent, and in the western bloc countries 38 percent. Meanwhile, production increased 29 percent, but could not keep pace with demand. Subsequently, sulphur stockpiles steadily shrank from 1 million tons in 1964 to .3 million tons in 1967.

Texas Gulf raised its posted price of sulphur by $2.00 a ton in response to the increased demand in 1964. The other U.S. producers and Mexican producers followed suit, but the Americans continued to give discounts in markets where Mexican and Canadian sulphur was present. The sharp increase in demand coupled with a wide differential between foreign and American sulphur induced the American companies to export 2.67 million tons in 1965, an all time industry high.

The attractive export markets consequently caused the domestic market to suffer. The government rectified the situation by limiting Frasch exports. Sulexco and the government worked out a rationing system in 1966 for the industry's export trade on an individual country basis. The only adverse effect of the rationing was an acute shortage in countries who had depended on an additional Pan American supply which had been cut due to a plant failure.

The Mexican industry raised their price on sulphur delivered to the U.S. by $5.00 a ton in 1966. The Americans adjusted their domestic price by eliminating allowances and manipulating transportation and handling charges. The continued increase in demand finally forced the American companies to raise their domestic prices in December 1966. Freeport raised its price on dark sulphur f.o.b. at Port sulphur by $2.50 per ton. Texas Gulf also increased its domesticated price by $2.50 per ton to $28.00 per ton for bright sulphur f.o.b. mines.

Pan American then announced a $10.00 per ton increase for its sulphur sold in the United States which was to go into effect on January 1, 1967. Gulf Sulphur also increased prices on contracts which came up for renewal. In general, foreign prices were well above the domestic market prices. In 1966, export price for U.S. Frasch sulphur (bright) for f.o.b. U.S. Gulf ports was $39.00 per ton. Mexican Frasch sulphur and recovered sulphur were even higher than the American prices.[141]

Two more price increases were experienced in 1967 as the shortage continued. Gulf port prices increased by $4.00 per ton f.o.b. in April, and then aonther $5.50 per ton in October. Freeport remained the price leader throughout the year demonstrating its dominance in the American industry at this time. The increased price still did not slow consumer demand so an allocation systems was created by the major producers. Texas Gulf limited deliveries to 75 percent of their 1965 level in September of 1966. In 1968, Texas Gulf limited its deliveries to 65 percent of its 1965 level. Freeport also began limiting deliveries to 90 percent of their base tonnage in 1967.

Export prices increased again in 1967 as Pan American raised its common-type sulphur to $50.00 per ton for its regular customers, and to $55.00 per ton for spot sales f.o.b. Coatzacoalcos, Mexico. Bright sulphur prices were raised to $52.00 and $57.00 per ton on the same basis. Canadian recovered sulphur was selling for $56.50 per ton f.o.b. in Vancouver.

In 1968, the shortage came to an end as non-communist country production exceeded shipments. Increased outputs of Canadian recovered sulphur and both American and Mexican Frasch sulphur were important in reversing the shortage as was the leveling off of U.S. consumption. In late 1968, western European prices were reduced by $2.00 per ton. In January 1969, Canadian and domestic markets saw the same kind of price reductions.

The shortage had sparked renewed interest in off-shore sulphur exploration. The Freeport operation at Grand Isle had been the only off-shore mine in the industry. However, the original Grand Isle concession was not the only lease provided to Freeport by Humble Oil. There was also a proven concession on the Grand Isle, Block 16 property, and a prospective concession located on the West Delta, Block 30 property.

In 1968, the Grand Isle, Block 16 property was brought into production by Freeport. The $25 million plant was named Caminada, and was located in fifty feet of water six miles off the Louisiana coast. The actual sulphur deposit was mined at a depth of 1750 feet below sea level. These were the only two offshore complexes put into operation with the West Delta, Block 30 land not being exploited.

However, a great deal of offshore property had been obtained for further exploration. In the shortage year of 1965, the United States Bureau of Land Management awarded leases for the exploration of sulphur on 72,000 acres of outer continental shelf located some forty to eighty miles from the Galveston-Freeport area.[142] The submerged shelf was found at depths of 110 to 180 feet. The leases were obtained by competitive bidding between seven major companies and combines. This bidding produced an average cost per acre of $468, highest cost of any outer shelf property, except those pertaining to certain oil and gas drainage rights. The leases were to last for ten years, with the federal government receiving either 10 percent of the gross product or value of sulphur at the wellhead, but never receiving less than $2.00 per long ton of sulphur.

This high cost of initial investment was the factor which deterred the extensive mining of far offshore sulphur. Drilling costs, facilities' building and operation costs, and transportation costs all increase well above those of near or onshore plants, and have subsequently retarded the development of far offshore Frasch operations.

The reopening of abandoned Frasch mines was another development brought about by the shortage of sulphur, and was partially responsible for its eventual end. These reopenings were largely brought about by new corporate entrys into the sulphur market.

Union Texas Petroleum Division, a subsidiary of Allied Chemical Corporation, led the entries by reopening the original Union Sulphur Mine at Sulphur Mine, Louisiana. Production began on September 18, 1966. Phelan Sulphur Company, a subsidiary of the John H. Phelan Oil Company, reopened the Nash Dome which had produced sulphur for Freeport between 1954 and 1956. The $2.5 million plant was built by Phelan in 1966, and produced 150,000 long tons with first shipments going out in 1967. Phelan then put the plant on a care and maintenance basis in 1969, as demand once again slackened and because the remaining reserves were believed to be substantial. The Hooker Chemical Company reopened the original Freeport Bryan Mound mine in June of 1967. Finally, U.S. Oil of Louisiana reopened the Freeport mine at Chacahoula in 1967 after it had been closed for five years. The dome produced 150,000 tons a year until the beginning of 1970 when operations were cutback to 60 percent. The dome which produced 1.2 million tons of sulphur for Freeport from 1955 to 1962, was believed to contain a four million ton sulphur reserve.

Poland also began contributing Frasch sulphur to the world market on a significant scale in 1967 and 1968 from plants at Jeziorak and Grzybow. The combined production of the two plants was 1,300,000 tons of sulphur per year.

A period of oversupply began in 1969 as consumption once again declined. A renewed competition for sales began, and stockpiles increased. Demand rose to 27.8 million tons in 1969, up 4.1 percent while supply grew by 5.3 percent to 28.9 million tons. This was the second year of surpluses.[143]

Price leadership by Frasch producers was almost eliminated in 1969. U.S. domestic prices still were officially posted at $39 to $40 per ton, but actual prices were running as low as $20 to $25 per ton on the market.

Production again was curtailed with marginal operations such as Freeport's second far offshore venture at Caminada being closed. Freeport also lowered production at four other plants. Texas Gulf responded by lowering production to under three million tons annually, and did not reopen its Texistepec plant in Mexico.

Duval, who had become the third largest U.S. producer by virtue of its new 1.5 million ton per year Culberson County plant in west Texas, was faced with the burden of two million additional tons of surplus unless they closed down some of their facilities. Their response was the closing of their Fort Stockton mine in Pecos County, Texas, and their operation at the Orchard Dome in May of 1970.

The Orchard mine had been producing 100,000 tons of sulphur per year up through 1969. However, the reserve was known to be almost depleted with only marginal flank deposits being mined. The dome was also a high water ratio dome compared to other Frasch producers, and consequently reopening was not planned.

The Fort Stockton mine was producing 1000 tons per day in mid-1968, with the total output for 1968 being 271,000 long tons. The mine was estimated to be a 350,000 ton per year producer, and was planned to be reopened when the market situation became favorable.

The Rustler Springs Mine in Culberson County was the largest mine known to exist in the non-communist world. The plant contained a forty million gallon reservoir with water delivered by pipeline from a source forty miles away. The plant was determined to have between forty-six and fifty-seven million tons of reserves, and the capability of producing 1.5 million tons of sulphur per year. The sulphur was shipped by rail to Galveston, Texas, some 900 miles eastward. The sulphur could then be shipped to terminals at

Savannah, Tampa, or Wilmington. Duval remained competitive in the early seventies, despite the high overheads encountered in operating this plant.

The surplus of sulphur was added to significantly in March of 1970 when huge stocks of Canadian recovered sulphur reached the market. The Canadian stocks had risen to 2.2 million tons with the at mine price being $10.00 or less, and the f.o.b. export price at Vancouver being $18.00 a ton. Sulexco was now offering its export sulphur at Rotterdam for $27.00 per ton, but with the influx of Canadian sulphur exports began to decline toward the volume of imports entering the United States. Mexico also was adversely affected by this new influx of cheap sour gas sulphur, and responded by closing several of its operations.

The rest of 1970 saw the continued deterioration of the market price with the Frasch producers nearly being eliminated from the foreign market. The domestic market was also suffering due to the flood of by-product sulphur from Canada. The result was the operation of the Frasch plants at nearly a zero profit margin.

Freeport asked for an import duty to be levied against the Canadian by-product sulphur saying that the Canadians were selling their sulphur under cost, and covering their actions by manipulating their balance sheets.[144] No action was taken against the Canadian sulphur which was now selling for as low as $5.00 per ton f.o.b. to new customers.

The demand for natural gas also rose at this time primarily due to a greater demand by the United States. Canada processed more sour gas, and opened six more recovery plants all producing about 350,000 tons per year. Six other plants were enlarged to an additional 20% of initial production for an increase of 600,000 tons.

Canada had become the world's leading exporter of sulphur with its output growing to seven million tons a year. The U.S., who had produced 7.15 million tons in 1969, only produced six million tons in 1970. Meanwhile, U.S. imports were seen to be up from 1.7 million tons in 1969 to two million tons in 1970. The Frasch producers looked toward the federal government for protection from imports to retain their domestic market.

Meanwhile, Alberta was devising better ways to ship their combined sulphur stocks from separated points of production to Vancouver in order to streamline their industry. A central stockpile was planned to service all companies operating in Canada. Twenty-four members' stocks were to be kept track of by a computerized accounting system.

The low price of sulphur also took its toll on the one time sole possessor of the market. In November 1970, the Sicilian sulphur industry went out of business with the complete shut down of all its mines.

The oversupply of sulphur worsened in 1971 as competition increased mostly due to Canada and Poland.[145] Canada had produced 4.4 million tons of sulphur in 1970, and had produced 5.8 million more tons by August 1971. The distribution of this output saw 3.5 million tons reaching the market with 1.1 million tons of this as free aid sulphur to Canadian industries as dictated by the government. The remaining 2.3 million tons were added to a six million ton existing stockpile. Projections were made at this time which foresaw a nine million ton production in 1975, and a twelve million ton production by 1980. Stockpiles would amount to twenty million tons in 1975, and sixty million tons in 1980. Canada would easily control the market with such stockpiles.

The gross excess of stockpiles arose due to the involuntary nature of the supply of by-product sulphur rising far ahead of demand. The greater amount of natural gas demanded caused the increase in natural gas produced, and its final increased sweetening. The huge stockpiles were the end result of this chain of events.

The price was effectively kept low by the abundance of the Canadian by-product sulphur. The posted price f.o.b. in Alberta was $6.00 per ton, and at Vancouver $17.00 per ton. Canadian sulphur was selling for $22.00 per ton in Europe while Frasch was $26.00 per ton at its export terminals. Alberta then decided to support the sulphur market by stockpiling greater quantities, and selling only smaller amounts when the market was favorable for $15.00 f.o.b. Alberta.

The United States and Mexico continued to take measures to remain competitive in the market. Texas Gulf shutdown its Gulf Dome which produced 90,000 tons per year. Mexican production declined by .3 million tons. Gulf Sulphur lowered production at its Jaltipan mine, and closed their facilities at Salinas.

The international sulphur producers met in August 1971 to reach an agreement on the restraint of output, and to fix a floor price to offer consumers. Higher prices were foreseen in the near future, and were expected to rise at a rate of five percent per annum with growth in demand. The sulphur surplus was also expected to continue. The companies resolved to limit sulphur rates through a cartel-like pact formed between Poland, Mexico, France, and Alberta. The United States was unable to join due to American anti-trust laws. The countries agreed to unilaterally limit sales in response to market forces, and Nixon's price freeze. Maximum annual sales were determined to be 1) Canada 3.8 million tons, 2) France 1.9 million tons,

3) Poland 3.3 million tons, 4) Mexico 3.3 million tons, and 5) the U.S. 6.4-7.6 million tons. These figures represented only sixty percent of world consumption which allowed leeway for the producers to meet demand.[146]

The market saw the lowest prices in twenty years in 1971, with the Frasch producers operating at distress levels. The Polish and Canadians enjoyed an increase in production levels and profits. Environmental sulphur recovered from SO_2 and other pollutants associated with industry also began appearing on the market. The total of all forms marketed in 1971 was 9.48 million tons. The U.S. did become a net exporter of sulphur in 1971 after a three year period of being a net importer.

In March 1972, Texas Gulf and Freeport raised prices against the trend. Texas Gulf's increase was $3.50 per ton while Freeport's increase was only $3.00 per ton. The increase was to counter Mexican dumping of sulphur on the lower states between Florida and Arizona. This area was also isolated from the Canadian supply. The next month Freeport withdrew the increase due to market conditions with Texas Gulf following suit. Both companies believed the long term effects would be detrimental to their interests, and therefore they dropped the increase.

Freeport continued to diversify from sulphur in early 1971 by operating through the Freeport Minerals Company. They began processing nickel and cobalt at their Greenvale complex in Queensland, Australia. They also began exploiting copper in Iran and Indonesia as well as continued expansion in kaolin, chemicals, potash, and Mexican asbestos.

Freeport and the other Frasch producers were also planning strategy for the near future. They realized that recovered sulphur would soon hold sixty percent of the market. The companies planned to operate their barely profitable large domes, and discontinue operation of all marginal domes.

The continued oversupply had kept the sulphur prices down in 1972 although consumption had increased. The United States shipment distribution domestically was: Frasch 55%, recovered 17%, all other forms 10%. Frasch exports increased 23%, but were still at the low level of eighteen percent. Imports were down 15% while stocks were reduced by nine percent.

Mexican sulphur sales were also down in the first half of 1972 by some 20%. The industry produced 482,786 metric tons of sulphur of which 440,300 tons were Frasch produced while 29,142 tons were produced by recovered sour gas, and 13,344 tons came from volcanic origin. Mexican exports declined over the same period.[147]

In February 1973, Texas Gulf was followed by Freeport in raising ton prices by $3.00. The effects were mostly felt by the Gulf coast, the South Atlantic seaboard, and up the Mississippi River to St. Louis which in effect was 90% of Freeport's customers. The companies were able to do this because demand was up, and the U.S. Tariff Commission had stopped the dumping of Mexican sulphur on the U.S. market. Anti-Canadian dumping tariffs were also planned for enactment. The increase brought the price f.o.b. at Tampa to $28.00 which was actually $17.00 less than the 1969 price.[148]

The world market began to see some new developments in 1973. Mexico began trading with China and supplied it with 50,000 tons of sulphur on a six month contract. The natural gas supply began to tighten, and U.S. imports of Canadian and Mexican sulphur dropped by fifteen percent. This hinted to a change developing in the sulphur supply and demand pattern.

Canada raised its price to $9.00 per ton f.o.b. Alberta and British Columbia a $2.00 increase. The Canadians wished to invade the Florida market, but were plagued by shipping problems. The Canadians stored their sulphur in the form of slate because of the enormous size of their stocks which disallowed liquid storage, and because slating did keep dust down and permit easy flow when handling the sulphur. However, the slated sulphur must be reliquified in Florida. This fact along with the distance of shipping to Florida were holding back this segment of the Canadian industry's growth.

The hearings conducted by the U.S. Treasury department found Canada guilty of dumping sulphur on the U.S. market. The dumping occurred from May 1971 to February 1972. Texas Gulf and Canadian Occidental were absolved of guilt.

U.S. Frasch sulphur increased twice in 1973. The increase was three dollars a ton each time. Problems in slating Canadian sulphur increased their f.o.b. Vancouver price to $21.00 per ton. Their North European prices were raised to a range of $27.00 to $29.00 c.i.f. per ton. Mexico, France, and Poland posted the same prices as Canada for their liquid sulphur c.i.f. North Europe. U.S. Frasch solid bright f.o.b. Gulf was $23.00 per ton, and U.S. Frasch liquid bright c.i.f. North Europe was $30.00 per ton as of October 1973.

The increased Frasch prices of 1973 were caused by a substantial increase in the demand of U.S. fertilizer industry. Eleven million long tons were marketed, an increase of 8% over 1972. Frasch contributed 69% of the sulphur, recovered sources 21%, and all other forms 10%. Frasch sulphur held 53% of the domestic market where consumption had risen by 6% to 56% of the sulphur produced. The average price per ton of Frasch sulphur sold for $18.26 per long ton.

Freeport reported earnings of $32.9 million for 1973 which almost doubled their 1972 earnings of $17.1 million. Freeport's output was down 79,000 tons from 1972 at 3.3 million tons, but they also bought and sold 200,000 additional tons of recovered sulphur. Their Frasch production came from the Grand Ecaille, Lake Pelto, Grand Isle, and Garden Island Bay operations. Both Grand Ecaille and Lake Pelto were described as nearly economically depleted in April of 1974.

Canada instituted a one-third increase upon its f.o.b. mine price increasing it from $15.00 to $20.00 per ton in April of 1974. The Canadian export price increased into a range from $25.00-$45.00 per ton f.o.b. Vancouver. Canadian stockpiles continued to grow with projected year end stocks to equal 15 million tons. Canada required an expansion in their slating capacity and improved rail transportation to reduce these stocks as well as increased slate storage capacity to handle the projected increased stocks.

The American major producers, Texasgulf Inc. and Freeport, correspondingly raised their domestic sulphur prices by $5.50 per ton following the increase by Canada. Freeport also announced an increase in their handling, storage, transportation, and insurance charges as reflected in their costs. The increase brought Freeport's regular dark sulphur price f.o.b. Port Sulphur, Louisiana to $33.50 per ton. The price of f.o.b. Tampa terminal sulphur became $36.50 per ton serving the Florida market which had become the world's largest sulphur market. Prices to other markets were based on transportation costs to those markets. Texasgulf's prices were similar to Freeport's, and both companies' price schedules were subject to U.S. government price controls and contract provisions. The American increase was only an 18% increase compared to the Canadians' 33% increase.

Freeport further expanded its diversified interests in 1974 by installing a 160 ton a day sulphuric acid plant at Port Sulphur fed by stack gases of the port's sulphur cleaning operation. Freeport also was operating a 1.4

million ton per year phosphoric acid plant at Uncle Sam, Louisiana. The plant used 615,000 tons of sulphur per year in 1974, and was supplied by Freeport's Port Sulphur facilities.

Overall Frasch sulphur controlled - 69% of the domestic market in 1974 by marketing 11.5 million tons of brimstone.[149] Domestic consumption had increased by 10% over 1973 levels with the increase attributed on the most part to the continued increase of demand in the fertilizer industry.

Total production of sulphur in the U.S. exceeded demand for the eighth straight year in 1975.[150] The industrial demand weakened with an especially disconsorting slow down in the demand of the fertilizer industry. Freeport consequently closed its Lake Pelto offshore venture. Frasch sulphur provided for sixty-five percent of the 11.25 million tons of sulphur produced in the United States in 1975.

Imports of sulphur decreased by sixteen percent, from 2.15 to 1.8 million tons. Stockpiles rose by thirty percent from 3.96 million tons in 1974 to 5.15 million tons in 1975. The average value of all elemental sulphur was $46.50 per ton versus $28.88 per ton in 1974. This was an increase of sixty-one percent.

In 1976, production was still ahead of domestic demand for the ninth straight year.[151] Industrial demand again was down, with the retarded growth in the fertilizer industry again present. Both imports and exports declined, and the U.S. again became a net importer of sulphur. The average shipment value of sulphur showed a slight increase in price in 1976 compared to 1975. Total production was down four percent from 11.25 million tons in 1975 to 10.8 million tons in 1976 with Texasgulf ending production at its Spindletop operation. Frasch sources supplied only 59% of the domestic market, a decline of 6% from 1975. The recovered sulphur industry increased by 3% to hold a 29%

portion of the market. Imports decreased by 18%. The average Frasch, and recovered f.o.b. mine plant price was $45.75 per ton while liquid Frasch sold for $65.00 a ton at the end of 1976.

Texasgulf's production level in 1976 was 2.5 million tons of sulphur contributed by the Fannett, Spindletop, Moss Bluff, and Newgulf (Boling) mines in Texas, and the Bully Camp mine in Louisiana. In March of 1976 Texasgulf suspended operations at Spindletop while opening a new mine at Comache Creek in West Texas. This facility was projected to be a 400-600,000 ton producer. Texasgulf also owned 34% of the Compania Exploradora del Istmo in Mexico, and four sour gas plants in Canada. Accompanying these sulphur producing ventures were their potash operations in Moab, Utah and Allan, Saskatchewan (40% interest), and a natural soda ash plant in Granger, Wyoming.[152]

In 1977, U.S. sulphur demand exceeded output with industrial demand up 10 percent.[153] The fertilizer industry's consumption of sulphur was up 7 percent, while U.S. production, exports, and producer's stocks all declined from 1976 levels. The United States was still a net importer of sulphur. The average shipment value per long ton of Frasch, and recovered elemental sulphur f.o.b. mine/plant was $44.75 per ton in 1977 down 4% from 1976. Domestic production by all sources declined from 10.71 million tons in 1976 to 10.53 million tons in 1977 a decrease of two percent. Recovered sulphur increased its share of the market from 29% to 33% while Frasch production dropped to 56% from 59%. Shipments of all forms equalled 10.79 million tons; a 5% increase over 1976. Imports were up 16% while exports declined by thirteen percent. A 9% increase was seen in consumption, while stocks declined by 5% from 5.56 to 5.3 tons. Continued research was performed to recover sulphur from smelter gases, and industrial stack gases. The Bureau of Mines also continued its work in the exploration of new industrial applications of sulphur. These new applications included:

ROADS - sulphur asphalt
- sulphur concrete
- sulphur impregnated concrete
- foamed sulphur

BUILDINGS - sulphur concrete
- sulphur impregnated concrete
- ceramics
- insulation
- foamed sulphur
- sulphur coatings

PACKAGING - sulphur impregnated cardboard
- foamed sulphur
- batteries

In March 1979, Texasgulf closed its Frasch operation at Fannett Sulphur Mine (a 167,000 ton per year producer) in Jefferson County, Texas due to a scarcity of local natural gas, escalating production costs, and depleted reserves. Another contributing factor was Texasgulf's large volume of stocks which exceeded 4 million long tons. The Fannett Dome had produced 3.5 million long tons over its lifetime.

The production capacities of the world producers of Frasch sulphur in 1978 appeared as follows:[154]

COUNTRY	COMPANY	APPROX. CAP.	REMARKS
U.S.A.	Duval Corp.	3,500,000 ltpa	Rustler Springs Frasch. Operation in Culberson County, W. Texas. Parent Company: Penzoil Co.
	Farmland	150,000 ltpa	Frasch producer. Subsidiary of Atlantic Richfield Co. Mine at Fort Stockton (Texas)
	Freeport Sulphur	3,000,000 ltpa	Frasch producer. Operations at Garden Isle (La.) (1.5 m. ltpa.; off-shore); Caminada (La.) (off-shore, but closed in 1969 and put on standby basis); Caillou Island (La.) (projected, given right conditions). Grand Ecaille (La.) (0.3 m. ltpa) closing this year.
	Jefferson Lake Sulphur Co.	400,000 ltpa	Frasch producer at Long Point (Texas) (0.4 m. ltpa)
	Texasgulf Inc.	2,500,000 ltpa	Frasch operations in Texas at Moss Bluff (0.3 m. ltpa); Newgulf (1.5 m ltpa); and Commache Creek (0.4 m. ltpa, opened Dec. 1975). Also Bully Camp, mine in La.
Mexico	Azufrera Pan-american SA	1,500,000 ltpa	Frasch mining at Jaltipan and Veracruz
	Cia. Exploradoradel	1,300,000 ltpa	Texasgulf Inc. subsidiary. Frasch sulphur at Coatza-coalcos
Poland	State owned	5,500,000 ltpa	Frasch mines at Grzybow, Jeziorak, and Baznia; open-pit Machow
Iraq	National Iraqi Minerals Co.	1,000,000 ltpa	Frasch type mine at Mishraq in conjunction with Poland

Demand exceeded domestic output in 1978 with industrial demand up eight percent.[155] The fertilizer industry increased its demand by five percent. Imports also exceeded exports. Frasch sulphur relinquished another five percent of production to the other forms of sulphur. Recovered sulphur was up 3% from 33% to 36%, and all other forms contributed thirteen percent. Price levels were $44.38 per ton mine f.o.b. and $67.42 per ton for liquid at Tampa.

January 1979 saw prices rising, and a shortage foreseen. Poland was now the number three producer of sulphur in the world followed by the U.S.S.R. The countries combined production was projected to rise by two million tons by 1980, but it still would not satisfy the demand of the communist countries.

August 1979 saw an increased tightness in the industry. Prices continued their slow increase. Canadian sulphur sold for $55-60 per metric ton f.o.b. Vancouver. Meanwhile, energy costs were hampering the American industry. The price at Tampa quoted by Freeport, Texasgulf, and Duval was $78.25.

In 1979, Freeport opened a new mine on a small deposit at Caillou Island. Terrebonne Bay, Louisiana. Production was expected to begin in 1981. This small high cost deposit of limited reserves was being exploited to balance supply at the current level of sales.[156] The Lake Pelto plant was disassembled and moved down to Caillou Island for operation.

The continued distressed market had begun to worsen in May. In November, Canadian Sulphur Export Corporation prepared delivery contracts entailing a $60.00 per ton f.o.b. Vancouver price. Liquid sulphur at Tampa was being sold by the Americans for $73.25 per ton.

The reason for the increased shortage was due to several contributing factors. A flood had partially closed operations at Poland's major open pit sulphur mine forcing a decline in production from 5.3 million tons to 4.8 million tons. British Columbian labor strikes had caused 100,000 tons of sulphur to be trapped in shipment. The unrest in Iran caused the discontinuation of its 500,000 ton per year sulphur production. An Iraqi contract was cancelled with Egypt for 100,000 tons per year. The continued demand of the fertilizer industry remained the main impetus behind the shortage with further expansion in the fertilizer market in North Africa, the Middle East, the East Communist Bloc countries, and China. Freights also doubled,causing increases in the price of a ton of sulphur. All these factors contributed to the bullish nature of the market which continued to be advantageous to the sulphur producers.

The extended strong demand caused France to open another recovery plant which produced 300,000 tons per year. Mexico also opened a 200,000 ton per year plant in 1979. November prices were posted as being:[157]

U.S. Frasch, liquid bright $95.50 Tampa.

U.S. Frasch, liquid bright $110.00-115.00 c.i.f. European.

French, Polish, liquid, c.i.f. North Europe $110.00-115.00.

Canadian solid slate, f.o.b. Vancouver spot sale - $130.00

Canadian solid slate, f.o.b. Vancouver contract avg. $110.00-115.00.

The United States finished the year as a net importer for the third straight year. Frasch sulphur contributed 52% to the market while recovered sulphur contributed 36% and all others contributed fourteen percent.[158]

The shortage continued into 1980 with petroleum companies seeking to recover more sulphur in refining operations. Meanwhile, Canada was vigorously "remining" its stockpiles. In August 1980, U.S. Frasch liquid sulphur bright reached a posted price of $127.50 per ton.

Freeport brought its Caillou Island mine, a 350,000 ton per year producer into production in December of 1980 two months ahead of schedule. The large power plant was mounted on a 200 foot long barge with a heating capacity of 2.5 million gallons of water daily. The sulphur was loaded into 2000 ton heated barges and transported to market in liquid form.

A close balance between worldwide supply and demand was seen in 1980 due to reduced European consumption. The reduced demand in Europe was attributed to recession, labor problems in Poland's shipping industry and wars in the Persian Gulf. These factors combined with high U.S. demand and reduced refinery production of recovered sulphur caused stocks on the Gulf Coast and in other principal locations to be reduced.

Freeport saw a third quarter reduction of 80,000 tons of stocks which continued into the fourth quarter. The company also recorded record earnings in the fourth quarter of 1980 which amounted to $38.58 million compared to $25.99 million for the comparable quarter of 1979. Total earnings for the year were also at record levels equaling $147.40 million compared to $101.39 million in 1979. Domestic oil and gas earnings provided most of the earnings while sulphur was the largest agricultural mineral group earner.

The extremely strong sulphur market of 1980 brought profits up for Canadian companies as it had for Freeport. Aquitaine Company of Canada Ltd., a sour gas sulphur recoverer, recorded net earnings of $65 million (Canadian) which almost doubled their 1979 net earnings of $33 million. Their 1980 sales volume was a record 1.2 million tonnes, an increase of 65% over 1979.

Sales of Canadian sulphur were up 12% over those of 1979 with 7.136 million tonnes of sales being posted. A large increase in the export price had increased sales revenues from $197.6 million in 1979 to $354.9 million in 1980.

A one percent increase in the consumption of sulphur was observed in the U.S. in 1980 as 12.15 million tonnes were consumed.[159] Domestic production slipped by one percent at 10.37 million tonnes. Stocks of Frasch and recovered sulphur were down 27% to 3.09 million tonnes from stocks present at the end of 1979.

The 1980 source distribution of production was 54% Frasch, 34% recovered elemental, and 12% all other forms.[160] Frasch sulphur had increased its share of the production by 2%. Total shipments for all forms of sulphur in both domestic and foreign markets were 12.7 million metric tons in 1980 down 4% from 13.29 million metric tons in 1979. Frasch sulphur represented 44% of the domestically consumed sulphur, and 13% of foreign consumption.

In 1981, the major Frasch companies continued to diversify and expand. Freeport Minerals Company merged with the McMoRan Oil and Gas Company to form Freeport-McMoRan Incorporated. Freeport became the major stockholder by purchasing 81.5% of the new company's stock. The merger came about because of McMoRan's unexplored and undeveloped oil and gas prospects, and the new company was expected to become a substantial competitor in the oil and gas market. Freeport's oil and gas earnings accounted for 14% of their total revenue in 1979.[161]

The continued strong sulphur market enabled the newly formed Freeport-McMoRan company to record first quarter earnings of $48.96 million versus $43.07 million for the same quarter in 1979. Production at their new Caillou Island facility had improved steadily while a new $2 million plant was started into operation in Culberson County, West Texas. The company also finished their expansion of their Freeport Kaolin plant which totaled $23 million.

Texasgulf expanded its Lee Creek phosphate operation to a 850,000 tons per year capacity in 1981. The capacity was planned to be expanded to 1.02 million tons per year in 1982. Among the $180 million in improvements will be a new sulphur terminal. The next expansion of the facility will be to a capacity of two million tons of P_2O_5 a year.

Total U.S. sulphur demand exceeded domestic production for the fourth straight year in 1981 even though industrial demand was down from 1980 figures by 4% while the fertilizer industry was down by 7%. The world market showed a similar character.

U.S. production, imports and stocks all showed increases while consumption shipments, and exports declined. Stocks rose from 3.1 million tonnes in 1980 to 3.4 million tonnes in 1981. This was also the fifth year of U.S. net import reliance.

Sulphur for domestic consumption came mainly from domestic sources: Frasch 37%, recovered 32%, and all other forms (co-product sulphuric acid, pyrites, hydrogen sulphide, and sulphur dioxide) 12%.[162] The remaining 19% was contributed by both Frasch and recovered sulphur imports. Eighty-five percent of all the sulphur became sulphuric acid before being used by other industries, and 60% of the sulphur was finally utilized by the fertilizer industry.

Freeport-McMoRan Inc. announced fourth quarter earnings of $26.06 million for 1981 compared to $40.87 million for the corresponding period of 1980. Full year earnings were reduced from $176.36 million in 1980 to $159.37 million in 1981.

One of the factors for the reduced earnings of the fourth quarter was a 30% fall in sulphur sales caused by a severe down-turn in the farm economy which began at mid-year, and because of depressed production and sales in the phosphate fertilizer industry.

Production, in 1982, is expected to be 12 million metric tons in the U.S. while consumption is expected to be 14 million tons. Frasch sulphur will probably contribute a little less than 40% of the domestic supply while further importation of sulphur will amount to about 20% of the market.

American Frasch will remain as a small percentage supplier to the foreign market due to the highly competitive producers in Mexico, Canada, France, Poland, and Saudi Arabia. The war between Iraq and Iran will continue to disrupt this source of sulphur.

Saudi Arabia is a newcomer to the world sulphur market. Its sulphur is produced by the recovery techniques applied to its large supplies of sour gas. The major plants are located at Berri, Uthmaniyal, and Shedgum. The building of operations began in 1979, and first deliveries began this year. This year's production is expected to exceed 1 million tons.

Texasgulf is one of three companies which will handle the exportation of the sulphur with their operation being the Berri site. Exports will be delivered to the Mediterranean, East Africa, and India. Total control will be turned over to the Saudi Sulphur Company, one of the present partners, in 1984 when they will be ready to handle the entire country's facilities. India will be an especially favorable target for exportation since it was formerly completely dependent on Iraqian and Iranian sulphur.

Meanwhile, the current recession is lowering consumption in industry. In response, the Frasch producers have stopped exploring for new sulphur deposits, and are satisfied to operate at a moderate level of production to keep a tight balance between supply and demand, and subsequently keep the price of sulphur high. The western producers are all utilizing this practice, and due to this practice more consumers are looking towards Eastern European producers and pyrite suppliers for their sulphur needs.

The posted prices of sulphur as of May 1982 were:[163]

U.S. Frasch, liquid, bright, ex-terminal, Tampa $147.50

U.S. Frasch liquid, bright, CIF N. Europe $160-$165

French, Polish, liquid, CIF N. Europe $160-$185

Canadian, solid/slate, FOB Vancouver, spot $110-$115

Canadian, solid/slate, FOB Vancouver, contract (average) $110-$115

Frasch sulphur's position in the world market will continue to be infringed upon during this decade. There will be continued expansion in sulphur recovery from sources and processes such as smelters and coal gasification. This segment of production will maintain its share of the market, but not increase it because of logistical and technical constraints working against its production.[164] However, further diversification in terms of the number of major exporting nations (e.g. Saudi Arabia) will take place with Eastern Europe and the Middle East becoming gradually more significant factors. They will provide both native and recovered elemental sulphur in amounts which should equalize the difference between consumption and the traditional sources of supply.

Canada will be less of a strong factor in the market despite the exploitation of vast oil sands. A slow down in gas production will effect the Canadian production before the tarsand exploitation. The Canadians will continue to sell from sulphur stocks long after gas production has diminished. Their export performance will be dependent on their ability to improve and enlarge their handling and transport facilities. The Canadians may be moving to the pellatization of their sulphur for easier handling.

Combined sources such as pyrites will reassert part of their former performance, as long as no unexpected larger scale elemental sources are developed. In the meantime, the western world pyrite leaders, Spain, Portugal, and Italy will continue to sustain or increase the capacities of their domestic industries.

Anti-pollution sulphur will continue to increase in supply from its 2 million tons in 1980 to 5 million tons in 1985. The 1990 estimate is 8 million tons. This sulphur will continue to be sold on a small scale and in localized markets (e.g. California and the southwest). The supply from this and other new sources of sulphur will surpass the demand for these same sources.

The demand for sulphur should rise at a rate of 4.6% per year through 1990. Total world market consumption will rise at an estimated average rate of 5% according to these projected consumption figures:[165]

1982 - 55.99 million tons
1984 - 59.07 million tons
1986 - 61.89 million tons
1988 - 64.83 million tons

Frasch sulphur from the United States will probably diminish to contributing only 32% of the demanded sulphur in 1985. The reduction in the influence of Frasch sulphur will be directly connected to the abundance of sulphur recovered from sour gas as this is the major competitive force in the market. Canada's ability to solve her transportation and handling problems will be a very important factor in the marketing of Frasch sulphur for once these problems are solved more Frasch markets will be invaded in the United States by the Canadian sulphur.

The general economic condition of the United States will also be a major influence on the Frasch producers. Their tightly controlled market will suffer if demand is not increased by an improved overall economy. Undoubtedly the trend will be for the Frasch companies to further diversify as Freeport did when it merged with McMoRan in 1981. Oil and gas will be the most attractive areas of expansion.

The Frasch industry will be challenged by three problems which have been with the industry since its beginning. The first is the depletion of reserves. Every dome has a finite limit to the amount of sulphur which may be extracted. The only answer to this problem is to find new dome deposits. However, the uncertainty of the market, its bust to boom cycles, makes this exploration difficult. The cost of recovering sulphur from new deposits will also be high because they will undoubtedly be offshore projects. That is the second problem. The last problem is the ever increasing costs of energy to provide power to the plants. Herman Frasch encountered this problem with Alabama coal in the beginning of the Union Sulphur Company. He was luckily saved by the plentiful oil soon found in Texas. Today, the Frasch producers must find ways of keeping the water ratio as low as possible as no new cheap energy sources are seen on the horizon. In the distant future, small nuclear reactors would be one viable alternate energy source while the location of the Frasch producers would make them excellent targets for solar powered steam production for heating the well and producing electricity. However, the near future will demand the use of fossil fuels which the producers must use in the most efficient and conservative manner to remain an efficient producer of sulphur.

SUMMARY

Herman Frasch started the Frasch sulphur industry in 1896 by utilizing his patented hot water mining process. The process pumped super-heated water down to the sulphur deposit enclosed in salt dome cap rock, melted the sulphur, and then pumped the molton sulphur back to the surface. The original mine was located at Sulphur Mine, Louisiana in Calcasieu Parish (southwest Louisiana).

The Frasch industry expanded into one of few sellers, and remained geographically concentrated in east Texas, south Louisiana, and the southeast portion of the Isthmus of Tehuantepec, Mexico. Herman Frasch's company, named the Union Sulphur Company, enjoyed a complete monopoly on the market from 1896 to 1912 due to Frasch's patents. Freeport Sulphur Company entered the industry with their operation at Bryanmound in east Texas in 1912. Texas Gulf Sulphur Company appeared in 1919 with another east Texas operation at Big Hill. In 1925, Union Sulphur ended operations at Sulphur Mine due to the depletion of the dome's reserves. In 1928, Duval Texas Sulphur Company entered the industry followed by the Jefferson Lake Sulphur Company in 1932. These four sulphur companies have dominated the Frasch industry in the United States since 1932 with Texas Gulf and Freeport controlling nearly 90% of the market. Five other unsuccessful attempts to establish themselves as Frasch competitors were put forth by 1) Baker Williams 1935, 2) Standard 1953-1957, 3) Lone Star 1954, 4) Admiral 1956, and 5) The United States Sulphur Company 1960-1962.

Potentials that have been realized in the geographically concentrated industry have shown sulphur domes to be a scarce commodity as only 27 of 200 Gulf coast salt domes have produced sulphur. Only ten of these 27 domes have produced five million tons of sulphur. Today only three domes, Garden Isle, Grand Isle, and Newgulf (Boling) produce a million or more tons of sulphur a year.

The Frasch plant has grown more sophisticated since its inception at Sulphur Mine while the process itself has remained the same. Today operations are not only located onshore, but also offshore on platforms and floating on barges. Seawater is used as well as freshwater in the mining process. Computerized instrumentation is utilized for complete and accurate control of the mining facilities. The most important factor in a successful Frasch operation the water-ratio, gallons of water required to raise a ton of sulphur (usually from 1000 gallons to 12,000 gallons a ton), is lowered as much as possible by mudding programs to plug cavernous cap rock or bleed wells to drain off as much excess cold water which may be present in the cap rock as possible. The most important development in the industry in recent years was the change over to liquid sulphur transport in 1959. This mode of transport is cleaner, and more efficient than dry handling. It also changed the marketing techniques of the Frasch producers, and the sulphur market balance in general.

The Frasch industry has always been a direct seller of sulphur to its consumers, and is solely dependent on the demand of these consumers for the sales volume of their sulphur. The sale of sulphur has also been on a contract basis, and until 1959 sulphur prices were quoted as f.o.b. (free on board) mine or Gulf port. In 1959, the switch to liquid transport of sulphur caused prices to be quoted as delivery prices at regional terminals. Customer services provided by the producers to consumers were also increased when liquid transport was instituted, as were the length of contracts between producer and consumer due to the small stockpiling capacity of liquid terminals compared to the huge stockpiles of dry sulphur before 1959. The smaller stockpiling caused the agreement to be lengthened because the same amount of supply was transported at a slower, but more constant rate. Frasch sulphur for export has for the majority of the industry's life, been marketed through the Sulphur Export Corporation (Sulexco).

The marketing of Frasch sulphur, and the power of the Frasch producers in the sulphur market have changed over the years. Union held a near monopoly over the domestic market from 1907-1915 while supplying a third of the foreign market with elemental sulphur in agreement with its only other competitor, Sicilian Sulphur.

World War I brought increased demand for Frasch sulphur as the supply of Spanish pyrites was curtailed to the American sulphuric acid industry. The price of sulphur was kept voluntarily low at this time of great demand to assist the munitions and fertilizer industries. This demand also caused an oversupply of sulphur stocks to develop when the Spanish supply was reestablished. The Frasch producers, to remain competitive, adjusted their prices to the price of domestic and imported pyrites over the next decade. This pattern of price adjustment to pyrites continued for the next twenty years.

The American Frasch producers formed the Sulphur Export Corporation in 1922 to negotiate a world sulphur agreement with the Sicilian Consortium, the marketer of the Sicilian sulphur industry. Their negotiations formed a cartel which allocated 75% of the world market to the American Frasch producers and 25% to the Consortium. The two parties met periodically to fix prices, terms, and sales conditions for their product. This agreement lasted until 1932 when the Sicillian industry was nationalized. A similar agreement was then entered into by Sulexco and the nationalized industry in 1934.

The entry of Duval and Jefferson Lake had little effect on the posted price of sulphur which changed only once during the period of 1927 to 1946. Their entry did force the two big companies (Freeport and Texas Gulf, Union had depleted its reserves) to relinquish both foreign and domestic markets in order to retain a stable market price. The entry of Jefferson Lake also brought about campaigning for equitable taxation of Frasch sulphur production in Louisiana which was successful in keeping the state's sulphur competitive in the domestic and world market.

The industry remained stable through the depression due to cooperation between all the producers throughout the world. In 1939, Sulexco cancelled all agreements with Italy due to war. The war again stimulated the Frasch industry. Production rose while stockpiles were reduced.

A period of shortage began immediately after the end of World War II as the chemical industry expanded rapidly and the Korean War demanded large amounts of sulphur dependent war products. Controls were placed on the industry to alleviate the shortage while new sources of elemental sulphur began to be developed. The first major new contributor of elemental sulphur was the Mexican Frasch industry which undercut American prices at domestic ports, and forced the Americans to reduce their prices to remain competitive. The Mexican industry developed into an industry controlled by Mexican nationals, and profitable for both its Mexican and American investors.

The recoverage of elemental sulphur as a by-product from sour natural gas began in the 1950's and showed a marked effect on the industry in 1959 when a period of surplus began in the sulphur market. Canada was the largest recoverer of by-product sulphur due to its large sour gas fields of Alberta, while France became the second largest, and took over a considerable portion of the western European market. Canada became the world's leading exporter of sulphur due to their production of recovered sulphur.

The Frasch producers began to diversify and expand during the 1950's with prominent expansion into the Canadian recovered sulphur industry by Texas Gulf and Jefferson Lake. Jefferson Lake also expanded into petrochemicals. Duval and Freeport expanded primarily into potash, metallic ores, phosphates, and kaolin. All of the Frasch producers entered the oil and gas market except for Duval.

Sulexco was reestablished by all four Frasch producers in 1958 to improve Frasch sulphur's stance in the foreign market. However, Frasch sulphur lost 35% of its share of the market to competitors between 1960 and 1963, and returns reached twenty-year lows on both the foreign and domestic markets.

A period of shortage began in 1964 due to a rapid increase in both foreign and domestic demand largely accounted to the fertilizer industry. The Frasch reserves were low due to the slackened period of production between 1958 and 1963, and inadequate to meet the demand. Production was increased, but fell well behind demand for the period. Stocks were decreased significantly while prices were almost doubled, and shipments by U.S. Frasch producers were rationed to achieve a balance between supply and demand. The balance was finally achieved in 1968 due to increased world production especially in Canada, and due to a major decrease in consumption.

A period of oversupply began in 1969 and continued through 1976. Canadian sulphur continued to enter the sulphur market in increasing amounts in 1970. The Canadian, French, Mexican, and now Polish producers nearly eliminated the U.S. from foreign markets in 1970 by providing plentiful supplies of sulphur to easily and cheaply reached markets. The U.S. responded by closing down more facilities, and looking toward the federal government for protection from foreign dumping of sulphur in the domestic market.

The international conference of sulphur producers in 1971 helped ease the sulphur conditions of the world market by agreeing on restraint of output conditions, and a fixed floor price to be offered to consumers. This action came in another year of all time low prices. The Frasch industry was assisted by these measures, and by legal rulings by the U.S. Federal government which stopped both Mexican and Canadian dumping of sulphur on the U.S. domestic market. A strong fertilizer industry produced price increases by both American and Canadian producers in 1973. The fertilizer industry remained strong in 1974, but fell off in 1975 which caused an accumulation of stocks in the Frasch industry. The Frasch industry was also losing more of the domestic market which by 1976 had fallen to 59% compared to 69% in 1974.

In 1977, increases in industrial consumption especially in the fertilizer industry brought demand above production in the United States. This increase continued into 1978 along with a slow rise in prices. In 1979, a shortage began to develop in the world market due to disruption in foreign supplies, and an expanding fertilizer market in developing countries. The shortage has continued into 1982 with a tight balance of trade being kept between supply and demand by the Frasch producers.

The future of the Frasch industry will see more of its market being encroached upon by all forms of sulphur, until it will hold only 32% of the market in 1985. Improved transportation systems in Canada could cause even more of the frasch domestic market to be lost by the end of the decade. Frasch sulphur will remain the producer's prime agricultural mineral commodity, while other mineral interests especially oil and gas will assume a much greater role in generating revenue for the Frasch producer. The industry faces three problems which have been present since its inception and will remain the most influential in the future:

1) depletion of existing reserves, 2) high fuel costs for driving the power-plant, and 3) market uncertainties that stifle exploration of new sources. Improved marketing strategies, customer service and technical advances in increasing the water ratios of the producing domes will be the only viable solutions to the challenges facing the Frasch industry in the years to come in order to keep it an efficient producer of sulphur.

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